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Analysis of surface roughness in the Sveta Magdalena paleo-landslide in the Rebrnice area

Analiza hrapavosti površja fosilnega plazu Sveta Magdalena na območju Rebrnic

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Abstract

In the geomorphologic analysis of the Rebrnice area, SW Slovenia, we used a morphometric indicator of surface roughness, which proved to be very useful in the study of the Sveta Magdalena paleo-landslide in the Rebrnice area. For the investigation of the surface roughness on the Sveta Magdalena paleo-landslide and its nearby area, we used two methods in GIS: slope variability and the Terrain Ruggedness Index (TRI). As an input for the analysis of roughness, we used digital elevation models (DEMs) with a resolution of 3 m × 3 m (resampled from 1 m × 1 m cells) obtained by airborne laser scanning.

Based on the analysis of the surface roughness we identified typical morphological characteristics that may reflect the mass gravity flow deposition. With the proper visualization (symbology) we can recognize lobate and fan-shaped forms of the bodies, increased roughness at the edges and at the forefront of the sedimentary body, marginal levees at the edges and arcuate levees in the middle part of the sedimentary bodies.

Key words: surface roughness, lidar, GIS, paleo-landslide, debris flow deposit

Izvleček

V okviru morfometričnih analiz smo na območju Rebrnic uporabili morfometrični indikator hrapavosti površja, ki se je izkazal za zelo uporabnega pri preučevanju fosilnega plazu Sveta Magdalena na območju Rebrnic. Za preiskovanje površinske hrapavosti na fosilnem plazu Sveta Magdalena in njegovi neposredni okolici smo v GIS-u uporabili dve metodi: metodo variabilnosti naklonov (*slope variability*) in metodo indeksa TRI (*Terrain Ruggedness Index*). Kot podlago za analizo hrapavosti smo uporabili digitalni model višin (DMV) ločljivosti 3 m × 3 m (osnovna ločljivost je bila 1 m × 1 m), pridobljen z zračnim laserskim lidarskim skeniranjem.

Na podlagi analize hrapavosti površja smo prepoznali značilne morfološke karakteristike, ki jih lahko vsebujejo sedimenti drobirskega toka. S primerno vizualizacijo smo lahko prepoznali jezičasto in pahljačasto obliko telesa, povečano hrapavost ob robovih sedimentnega telesa, povečano hrapavost na čelu pahljače, ki lahko pomeni inverzno gradacijo v čelu drobirskega toka, obrobne grebene v pahljači ter usločenost grebenov v sredini sedimentnega telesa.

Ključne besede: hrapavost površja, lidar, GIS, fosilni plaz, sediment drobirskega toka

Introduction

Morphometric analyses and their visualization can be of great help in the characterization of the variability of the surface and are an excellent complement to traditional fieldwork techniques and geological mapping. Morphometry, which is defined as a quantitative measurement of landforms and provides an objective comparison of different segments of the Earth's surface is often used in identifying and defining the Earth's surface, modelling the surface processes and tectonic geomorphology.[1–3] Within morphometric analysis, in the Rebrnice area, or more precisely on one of the five sedimentary bodies – Sveta Magdalena paleo-landslide (Figure 1) – we used a morphometric indicator, that is, surface roughness, which is, besides the curvature analysis of the surface, very useful in studying and identifying paleo-landslides.[4–7] With the analysis of the surface roughness we wanted to distinguish the morphology of the sedimentary body from the surrounding morphology and accurately characterize the surface of sedimentary bodies.[8–10]

The article deals with the variability of the quantification of surface roughness, based on two methods: Slope variability[1] and the Terrain ruggedness index (*TRI*).[11] As the basis for the analysis of surface roughness, we used digital elevation models (DEMs) with resolution of 3 m × 3 m obtained by airborne laser scanning (Figure 1).[12, 13] With visual interpretation and field validation, we achieved greater consistency in determining forms of relief structures and their metric properties.

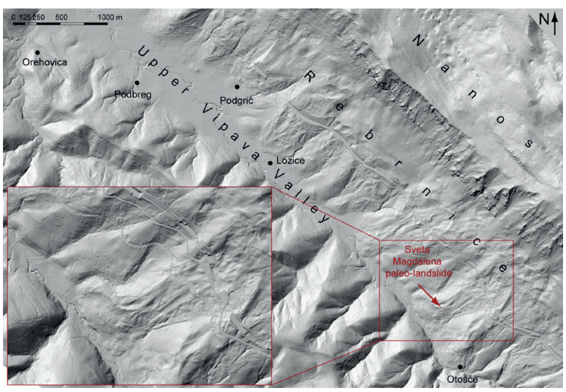

Figure 1: *Digital elevation model of large fan- and tongue-shaped sedimentary bodies in the Rebrnice area depicting the study area – Sveta Magdalena paleo-landslide. The image was generated from Lidar data rasterized to a resolution of* 1 m × 1 m.

Geologic setting

The research area belongs to a complex Eocene to Oligocene fold-and-thrust structure of the External Dinarides[14–15], with three nappes in the Vipava Valley region (Figure 2): Komen, Snežnik and Hrušica (listed from the structurally lowest to the highest nappes). The Komen and Snežnik nappes are composed solely of flysch, lying in the central part of the valley and in the Vipavska Brda (SW slopes). Mesozoic carbonates of Hrušica nappe are overthrusted on

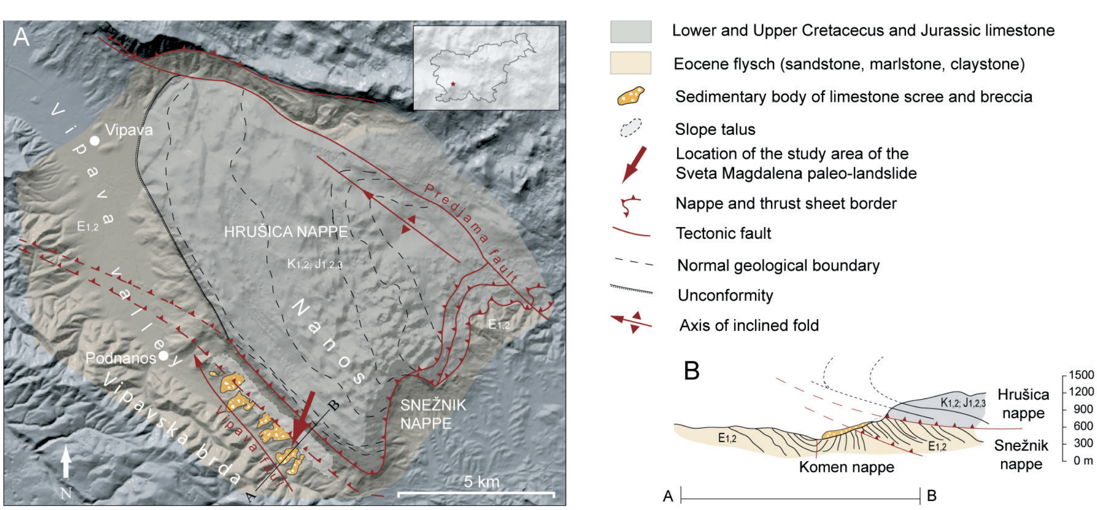

Figure 2: *A simplified geological map and cross section across the Upper Vipava valley; from Vipavska Brda to Rebrnice and Nanos; SW Slovenia.*[14, 17]

Snežnik nappe, represented by Tertiary flysch in the Rebrnice (NE) slopes of the Vipava valley. Geomorphologically, this thrust contact is reflected by steep carbonate cliffs in the upper parts of the slopes, while the middle and lower parts of the Rebrnice area, composed of flysch rocks, are gently sloping. The latter areas are covered by numerous fan-shaped Quaternary deposits[8, 16], some of which were deposited by gravity-flows.[8, 10] A large Neogene dextral strike-slip fault zone (up to 300 m wide) known as the Vipava fault is also present in the central part of the valley (Figure 1).[17]

Methods and materials

As a basis for the analysis of surface roughness, we used digital elevation models (DEMs) obtained with airborne laser scanning (ALS). A one-metre resolution DEM was obtained by a combination of adaptive triangulated irregular network densification – ATIN[17]; implemented in Terrasolid Terrascan 11 – and repetitive interpolation – REIN.[11, 19, 20] Lidar data with a resolution of a 1 m × 1 m cell were smoothed by the Focal Statistics Spatial Analyst tools, the size of the area of 3 m × 3 m cell.[13, 20] From the abovementioned digital elevation model we made out two information layers, namely the slope roughness variation method and the *TRI* method.[1, 11]

The slope variability method (here slightly modified to analyze the height instead of slope values, to emphasise the difference in relief) analyses the differences between the lowest and highest elevations in the selected area. By the Focal Statistics tool in ArcGIS, we made a map of these elevations, based on the digital elevation model (DEM) with resolution 3 m × 3 m (resampled from 1 m × 1 m). The final map (Figure 3B) shows the differences between the lowest and highest elevations in the area.

$$SV = S_{\max} - S_{\min} \qquad (1)$$

SV = Slope Variability output raster
S_{max} = maximum height value raster
S_{min} = minimum height value raster

The *TRI* method is based on the calculation of relief ruggedness, calculated from differences between the elevations in the cells in the window size of 3 m × 3 m. By the Focal Statistics tool, we produced the raster map of maximum (H_{max}) and minimum elevations (H_{min}), based on the same DEM. The *TRI* is therefore calculated as:

$$TRI = \sqrt{|H_{\max}{}^2 - H_{\min}{}^2|} \qquad (2)$$

TRI = Terrain Ruggedness Index
H_{max} = maximum elevations
H_{min} = minimum elevations

For both methods, the continuous colour map was used in ArcGIS to represent the data visually, to avoid classification into artificially made categories. Prior to selection of an optimal size range (3 m × 3 m), we tried to produce different size ranges (1 m × 1 m, 10 m × 10 m and 50 m × 50 m). The original size of 1 m × 1 m (high resolution) gave results which were too fragmented, and had excessive noise due to the network being too dense. In contrast, by choosing larger areas (10 m × 10 m and 50 m × 50 m) (lower resolution), the border was too blurred and the results again were not suitable for any morphometric analysis.

Results and discussion

According to the lithological diversity of the carbonate gravel (which belongs to the sedimentary body of the paleo-landslide of Sveta Magdalena) and of flysch base rocks (in the neighbourhood) the results of the slope variability and *TRI* were very useful. It turned out that the carbonate gravel of the sedimentary body has high slope variability and *TRI* values, which means that the sedimentary body of carbonate gravel exhibits a high degree of surface roughness. In contrast, the area made of flysch base rocks in the vicinity of the sedimentary bodies represents values of lower slope variability and *TRI*. Consequently, associate flysch represents an area with low surface roughness, that is, the surface in this part of the area is relatively smooth (Figure 3). Even from the shaded digital elevation model produced from

Lidar data (Figures 1 and 3A) it can be seen that the studied sedimentary body of the paleo-landslide Sveta Magdalena and the immediate surroundings represent a range of evidently variable surface roughness.

Slope Variability

The results of the slope variability method are visible in Figure 3B, representing the difference between the highest and the lowest elevations. The casts of colours were divided roughly into three levels: low, medium and high variability of slopes. The casts of light to dark pink correspond to smooth surfaces (e.g., the Razdrto–Vipava motorway; upper (NE) part of the slopes), the cast of blue-green colour correspond to intermediate values (between smooth and rough surfaces), and the cast of yellow-brown colours correspond to areas with rough surfaces. Colour visualization was found to be useful to illustrate the areas with low and/or high slope variability.

The case of the paleo-landslide of Sveta Magdalena shows that the values of slope variability on the northern, western and southern parts of the sedimentary bodies are extremely high. High values of slope variability can be identified only in the lower part (fan-shaped part) of the sedimentary body at the toe of the landslide, while in the upper part, just below the carbonate Nanos massif, carbonate gravels in the form of scree deposit prevail, therefore a more accurate separation of this part of the sedimentary body is not possible. At the edge of the sedimentary body, blue-green colour casts prevail. At the toe of the landslide, yellow-brown colour casts that show medium to high surface roughness occur. These are in sharp contrast with the light-pink and pink colours which represent a smooth surface. Sharp transitions of slope variability on the outskirts of the sedimentary body can be attributed to steep margins and correspond to the lithological boundary, which represents the boundary of the Sveta Magdalena paleo-landslide. The sedimentary body composed of carbonate gravel mostly represents an area with medium to high surface roughness, while the flysch rocks mainly comprise smooth areas with very low slope variability (Figures 3B and C).

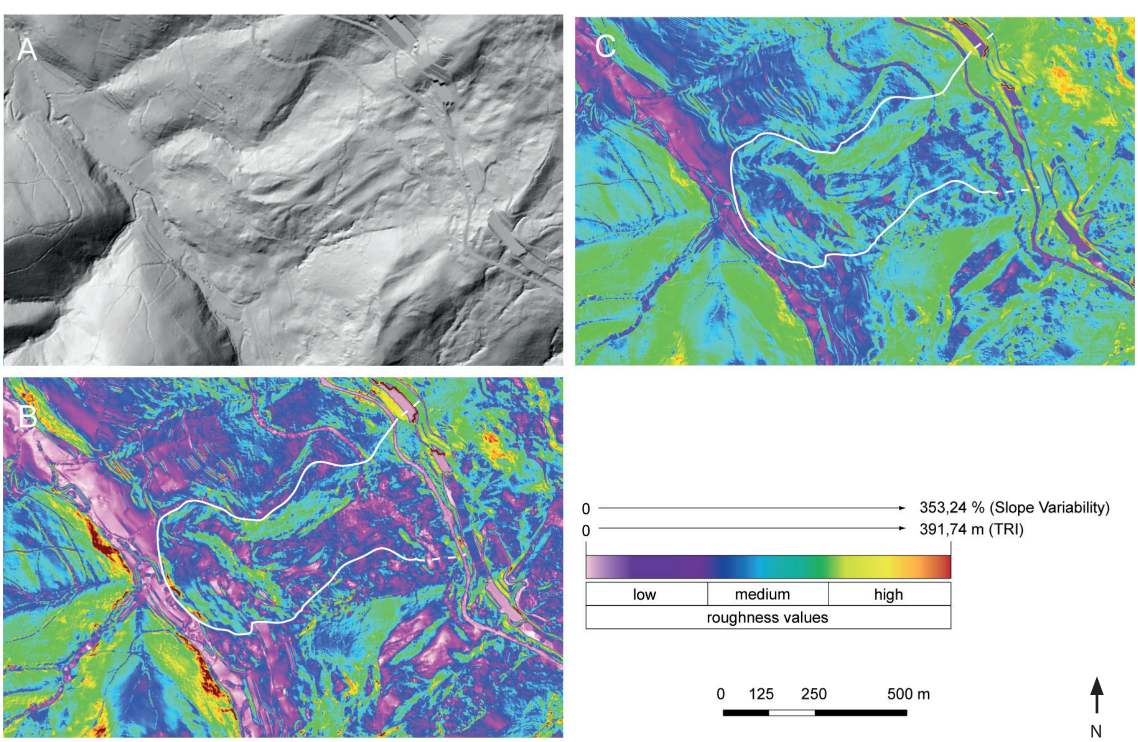

Figure 3: *Two sample output for surface-roughness calculation with (A) digital elevation model of the Sveta Magdalena paleo-landslide. (B) Slope Variability. (C) Terrain Ruggedness Index (TRI).*

Higher slope variability at the edge, and in particular at the forefront, of sedimentary bodies can be explained by the phenomenon of inverse graded clasts and blocks in this part of the landslide. Typically, the debris flows of the larger particles move towards the edge of the flow and in a direction vertical to the surface current.[21, 22] This may result in inverse particle size classification and consequently, greater slope variability.

In the middle part of the fan-shaped sedimentary bodies on the surface of the individual bands, which are approximately parallel to the edge (toe) of the landslide, we recognized medium to high slope variability (arrows in Figure 4), which may indicate the individual reefs. Major[21] suggested, on the basis of experimental studies, that debris-flow deposition and deposits can be affected by degree of water saturation. As water saturation can affect debris-flow characteristics and deposition, clearly unsaturated flows exhibit steep margins and quite equant shapes with a width/length ratio greater than 0.5. Several arcuate ridges can appear on the surface due to successive waves of flow overriding and shoving the debris to the flume mouth.

Furthermore, it is obvious that in the fan-shaped sedimentary body two major areas emerged where the slope variability is extremely low (areas marked in Figure 5A). Areas with low slope variability are separated by an approximately 400 m long strip of high slope variability. These two areas, which represent a small surface roughness and are separated by areas of high surface roughness, could belong to two different sedimentary bodies. If these two areas are analysed in more detail, it can be seen that, even within areas with low roughness, smaller areas appear with a relatively high surface roughness (arrows in Figure 5B). This surface roughness could be attributed to the arcuate levees in smaller dimensions, which appear on the surface. From the forms of the arcuate levees with high slope variability, the direction of the sediment transport stream (Figure 5C) can be supposed. On the basis of the two different orientations of the arcuate levees on the surface of the sedimentary bodies (within an area with a relatively small variation in the inclination) we can conclude that the Sveta Magdalena paleo-landslide, at least in the part of the fan-shaped sedimentary body, was most probably formed by two separate events, which were transported in the form of mass gravity flows[9, 10] down the slope in the Upper Vipava valley.

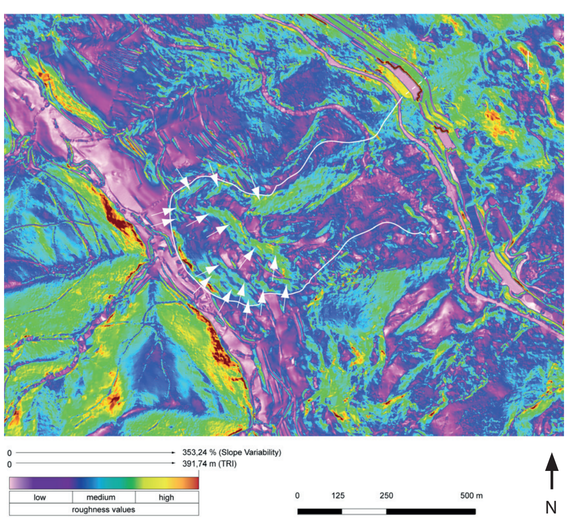

Figure 4: *The arrows on the figure indicate individual separate bands with medium to high slope variability that are approximately parallel to the edge of the sedimentary body of the Sveta Magdalena paleo-landslide.*

Terrain Ruggedness Index (TRI)

The results of the *TRI* are visible in Figure 3C. The cast of colours (similar to the slope variability) are divided roughly into three levels: low, medium and high *TRI*s. The cast of the light to dark pink colour corresponds to a smooth surface, blue-green colour tones correspond to intermediate values (between smooth and rough surfaces), and yellow-brown colour tones correspond to areas with a rough surface. Both methods give very similar maps (Figure 3), so the results for the *TRI* method can be similarly interpreted as the slope variability method. For this reason, only slope variability maps are shown in Figures 4 and 5. The latter method visually produces a larger range of data and is therefore preferred due to the more pronounced differences in relief roughness. One must, however, note that such a conclusion is based only on our study area and must be tested elsewhere. The results of both methods show that the surface roughness is the key variable in identifying the different forms of the surface and for the determination of the processes that have an effect on it.

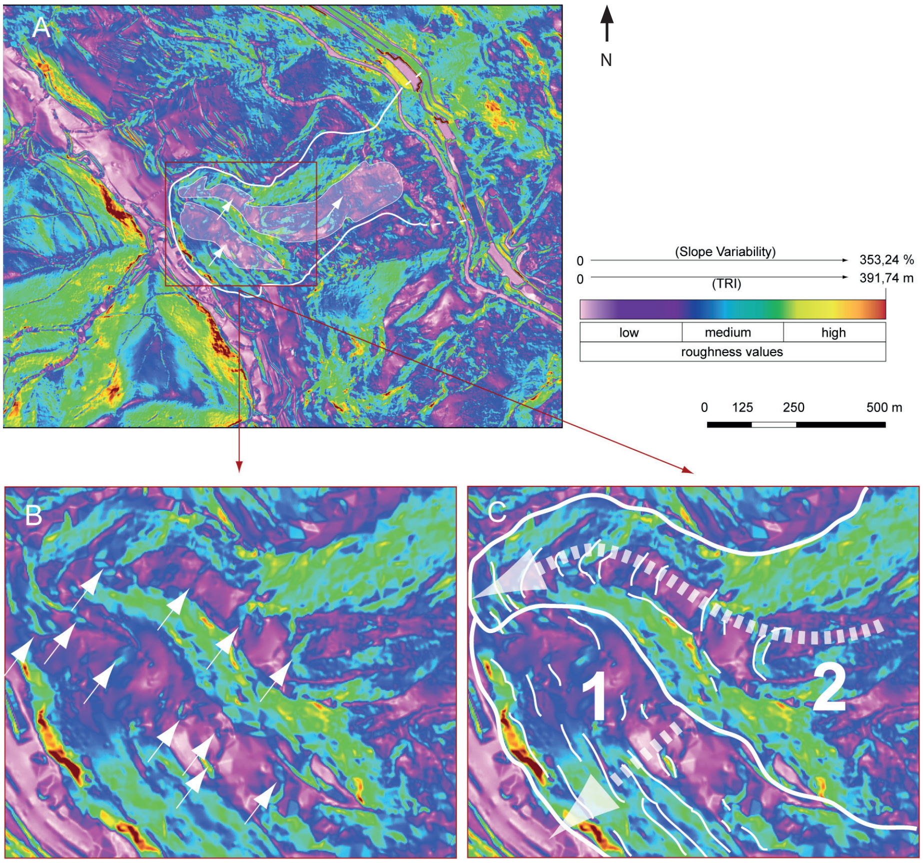

Figure 5: *(A) The indicated areas in the sedimentary body represent an area with low slope variability. (B) The arrows show individual and small separated areas with medium to high slope variability. (C) Approximate direction of transport of carbonate gravel, in the form of two debris flows (1: older and 2: younger) transported into the lower-lying parts of the Upper Vipava valley.*

Conclusions

It has been shown that the surface roughness in this part of the Rebrnice area primarily depends on the properties of the material (lithology). The findings are similar to those of Grohmann et al. who, in addition to material properties, have attributed varying surface roughness to the current and past processes, and to the time elapsed since the formation of the surface.[23, 24] The high contrast between the high degree of surface roughness of the sedimentary body of the Sveta Magdalena paleo-landslide and the smoothness of the surface belonging to the area near the sedimentary body represent two different lithological units: the carbonate gravel, which belongs to the sedimentary body of the Sveta Magdalene paleo-landslide and flysch rocks, which constitute the bedrock and are today in the base and in the immediate vicinity of the paleo-landslide.

With the visual interpretation and the field validation, we achieved greater consistency in determining the shape of the relief structures and their metric properties. The properties of the surface of the sedimentary body of the Sveta Magdalena paleo- landslide in the Rebrnice area were identified by a visual interpretation of the digital elevation model and with calculated indicators of surface roughness. With both methods, slope variability and the *TRI*, we have recognized typical morphological characteristics expressed in the mass gravity flow. With visualization (GIS symbology), we could recognize lobate and fan-shaped bodies, increased surface roughness at the edges of the sedimentary bodies (steep margins), marginal levees and arcuate levees in the middle of the sedimentary body. In addition, we identified in part of the fan-shape body, in an area with relatively low slope variability and low *TRI*, two groups of curving ridges in different directions. All of these identified elements in the sedimentary body of the Sveta Magdalena paleo-landslide suggest that the sediments were transported in the form of unsaturated mass gravity flow (debris flow)[21] (probably in at least two separate events in time).

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