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Extending Physical Geomorphometry into 3D: A Case Study on Domica Cave, Slovakia

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1

Abstract— We present a novel approach to physical geomorphometry applied to the Domica Cave system in Slovakia. Using a high-resolution terrestrial laser scanning point-cloud, we generated a 3D mesh model of the cave, enabling the application of the framework of physical geomorphometry. A central aspect of this study is the computation of unit total cave work, a specific subsurface variant of exogenous work. This metric links 3D cave physical geomorphometry with 2.5D surface geomorphometry and provides new insights into cave formation processes and their interaction with geomorphic evolution. To operationalize these concepts, we developed an automated methodology for defining the central line of the 3D cave model and systematically slicing it into transverse profiles. The results demonstrate the utility of physical geomorphometry in cave studies, offering a new perspective on subsurface geomorphic processes and their linkages to surface topography.

I. INTRODUCTION

Caves represent a unique geomorphic environment where traditional 2.5D surface-based geomorphometric techniques cannot be directly applied. Physical geomorphometry defined in [1] and [2] provides a robust theoretical framework for describing landform evolution in terms of energy, work, and force, integrating gravity principles with geomorphic processes. While 2D physical geomorphometry has been well-established, its application to 3D cave systems remains in early stages.

This study explores the application of physical geomorphometry to characterize the amount of geomorphic work recorded in a part of the Domica cave (Fig. 1). The cave is a part of 27 km long system formed inside a Triassic limestone plateau that spans the border between Slovakia and Hungary in Central Europe. By defining and applying the concept of unit total cave work (CW), we establish a novel approach to quantify effect of subsurface

geomorphic processes. Our methodology builds on prior work in digital terrain modeling and expands it into three-dimensional cave environments [3]. This study presents advances in the methodology and application of physical geomorphometry linking to the development of the overall theoretical concept introduced in another paper of the Geomorphometry 2025 abstracts [4].

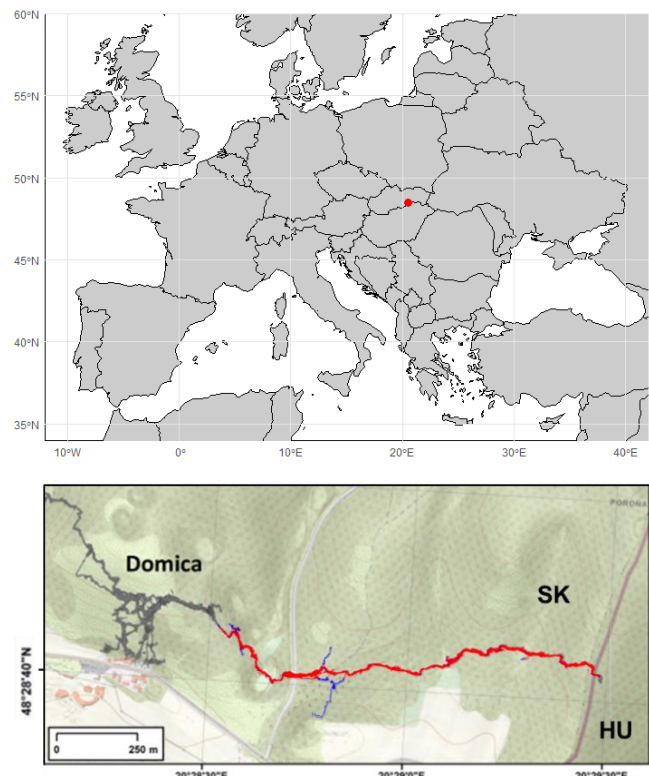


Figure 1. Location of the Domica cave and its part used in the case study (red).

II. DERIVATION OF BASIC CAVE WORKS

In [4], the **unit total cave work** (CW) is defined as a potential lowering of the surface by the collapse of the cave:

$$CW = (1m^3) \cdot \frac{V_{cave}}{A_{cave}} \rho \cdot g \quad (1)$$

where ρ is rock density, g is the acceleration of gravity and $1m^3$ represents the unit volume of material on the surface whose potential gravity energy is changed by the potential collapse of the cave (Fig. 2A). The unit total cave work (CW) quantifies the average change in gravity potential energy associated with $1m^3$ of denuded material, calculated from the total cave volume (V_{cave}) and its planimetric projection area (A_{cave}) following Eq. (1). Subsequently, it is possible to investigate how this cave work is distributed in the individual parts of the cave, represented by its transverse profiles through their passages. When we assign a unit width (1m) to each profile (Fig. 2B), the **total cave profile work** (CW_{tp}) will be given (for horizontal passages) by ratio of the profile area A_p and diameter of the profile ($= 2r_p$) that represents its map projection on the land surface:

$$CW_{tp} = (1m^3) \cdot \frac{A_p(.1m)}{2r_p(.1m)} = \frac{\pi}{2} \cdot r_p \cdot \rho \cdot g \quad (2)$$

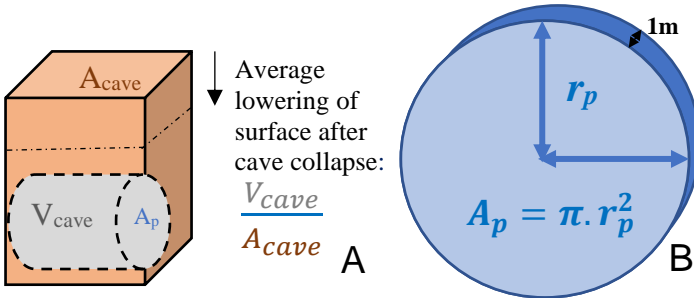


Figure 2. Derivation of cave physical geomorphometry: **A** Total cave work CW (1); **B**. Total cave profile works CW_{tp} (2).

In the general case of non-horizontal passages, the calculation of CW_{tp} incorporates the slope correction as shown in [4], accounting for both horizontal and vertical components of the gravitational work. The unit total cave work (CW) is conceptualized as a specific subsurface variant of exogenous work (ExW). In the context of surface geomorphometry, ExW is defined as the difference between maximum and mean elevation, representing the portion of past endogenous work (EnW) removed by exogenous processes [4]. By analogy, CW represents the elimination of EnW within the cave system that has not yet manifested at the surface — theoretically, it would be expressed in surface elevation changes following cave ceiling collapse. This CW framework enables a direct link between 3D physical geomorphometry of caves and the established 2D surface geomorphometry system and further supports the definition of

additional physical geomorphometric characteristics derived from transverse cave profiles (Fig. 2B).

III. METHODS

The research is based on a 3D cave model derived from 3D point clouds acquired during several terrestrial laser scanning campaigns [5]. The data provide a high-resolution 3D representation of cave morphology at the spacing of several millimeters. The 3D model used in this study was generated in the form of a triangulated mesh by Poisson surface reconstruction method [6] implemented in the open-source software CloudCompare [7] at 10 cm spacing of the mesh nodes. A 3D centerline of the cave corridors was extracted using a NeuroMorph [8] plugin in the open-source software Blender [9]. A computational algorithm traced the longest continuous path, representing the cave corridor. Smoothing of the line minimized distortions and ensured profile consistency. The 3D cave model was then systematically sliced at 1-meter intervals, with transverse sections generated perpendicular to the centerline in CloudCompare using a customized Python script of CloudComPy library [10]. The slicing algorithm adapted dynamically to curved and branching passages to prevent profile overlap and segmentation errors. Theoretical expectations suggest that passages with larger cross-sectional areas and lower slopes correspond to higher subsurface geomorphic work values, reflecting zones of intensified speleogenetic activity and preferential dissolution. Complex cave geometry was managed through clustering techniques, ensuring that multi-level sections were correctly categorized. The final slices were classified based on their geomorphometric properties and stored in GIS-compatible formats for further analysis in the Scene interface of ArcGIS Pro by ESRI. We calculated the unit total cave work CW (1) and the total cave profile work CW_{tp} (2) assuming the limestone rock density ρ of 2,600 kg/m³ and the gravity acceleration g of 9.80663 kg/m². The r_p was calculated from the slice area A_p by:

$$r_p = \sqrt{A_p/\pi} \quad (3)$$

All passages were considered horizontally inclined despite a gentle dip of the cave bottom from west to east.

IV. RESULTS AND DISCUSSION

Our study confirms that outlined physical geomorphometric principles can be effectively extended into 3D cave environments. The analysed section contained 1,862 transverse slices thus the section was 1,862 m long. The vertical range of the cave bottom was 7 meters between the start and the end of the cave section which is an average dip of 0.215°. This justifies the use of a simplified relation (2) for the calculation of CW_{tp} . The total volume of the analysed section of the cave (V_{cave}) was 68,476 m³, and the horizontally projected area (A_{cave}) was 14,232 m². Based on these

values, the computed average CW is 120.577 kJ per unit volume which corresponds to an average of 4.81 m of denuded material. Figure 3 demonstrates the CW_{tp} values distributed along the cave centerline, where passages with larger cross-sectional areas correspond to higher values of subsurface geomorphic work, reflecting zones of intensified speleogenetic activity. It is only one of the physical-geomorphometric indicators that can be used for a comprehensive segmentation of the cave passage, but even so, in Fig. 3, different regions can be seen, which are partly related to different features of surface morphology. In accordance with the development of the theory outlined in [4], we plan to supplement the characteristics of the passages with the measures of their asymmetry expressed in the directional cave profile work as well as the cave energy resulting from the roughness of its surface. Based on all these three physical-geomorphometric quantities, it will be possible to finally implement a comprehensive physically based segmentation of the cave. Comparison of the result of cave segmentation with physical-geomorphometric analysis and segmentation of land surface is our ultimate goal. This will allow us to test the hypothesis that the physical-geomorphometric properties of the cave could have some connection with the physical-geomorphometric character of the surface above it.

The findings, while preliminary, align with theoretical expectations and reinforce the link between cave evolution and subsurface as well as surface geomorphic processes. Here, cave evolution refers to the enlargement, collapse, and reshaping of underground voids through dissolution and mechanical processes, while subsurface geomorphic processes include material removal, structural failure, and sediment infill, influencing both underground morphology and surface topography. The CW metric thus provides a foundation for interpreting speleogenetic patterns and the broader evolution of subsurface landscapes.

Advancements in automated cave segmentation also improve the standardization of comparative analyses between different cave systems and enhance morphometric classification approaches. Furthermore, the established connection between 3D cave morphology and 2D surface relief broadens the potential for holistic landscape evolution studies, integrating subsurface and surface geomorphometry into a comprehensive analytical framework. While the planimetric area (A_{cave}) provides a direct 2D projection of the cave system, the calculated CW_{tp} values quantify the gravity work potential that would be released if surface collapse occurred. Thus, 3D cave geometry informs surface processes such as denudation rates, potential sinkhole formation, and broader landscape evolution dynamics.

Nevertheless, interpreting the calculated physical geomorphometric parameters requires careful consideration. Further methodological improvements should focus on better treatment of cave branches in a speleogenetic context and on properly handling vertical chimneys, which, due to their large volume, reflect a different type of geomorphological work than horizontal passages.

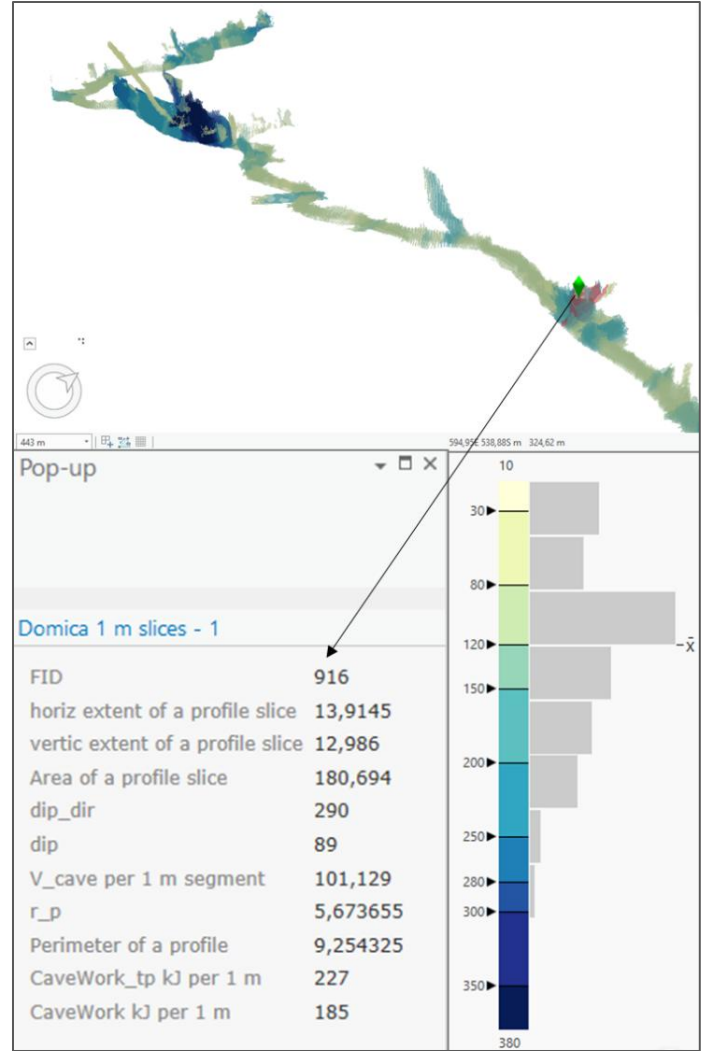


Figure 3. Total cave profile work (CW_{tp}) per unit length in kilo Joules along the cave centreline. The attributes used for calculation and assigned to each cave slice are shown in the pop-up window. The histogram illustrates the distribution of CW in the cave.

V. CONCLUSIONS

This study advances the integration of 3D physical geomorphometry into karst research. The development of the unit total cave work (CW) metric and its systematic computation along the cave centerline (CW_{tp}) offer a novel framework for quantifying subsurface geomorphic processes. The distribution of CW_{tp} revealed zones of enhanced passage enlargement corresponding to anticipated speleogenetic activity, particularly in wider and flatter segments. This reinforces the idea that 3D cave morphology retains measurable signatures of subsurface geomorphic evolution processes. Additionally, the proposed methodology offers a

framework for comparing different caves and standardizing cave morphometric classification.

Nevertheless, certain limitations should be considered. Interpretation becomes more complex where cave morphology results from multiple phases of accumulation and erosion, and the present model does not explicitly incorporate variations in rock resistance or solvability, which can influence the distribution of geomorphic work. Critical factors for the reliable application of this method include high-resolution 3D data, accurate centerline extraction, and consistent slicing of cave profiles. Deviations in model quality would significantly affect the reliability of CW values.

The findings reinforce the connection between subsurface cave evolution and surface denudational processes, offering a measurable link between underground void formation and surface topography changes. Future work should explore broader applications across different karst systems, consider vertical features (e.g., chimneys) separately, and further refine automation workflows for large-scale comparisons. For a comprehensive physical-geomorphometric segmentation of caves, it is necessary to refine the theory and methodology of expressing other cave energies, such as the (a)symmetry of the distribution of cave profile work CW_p and cave energy resulting from roughness characteristics. Furthermore, extending the analysis to consider additional types of geomorphic work, such as the kinetic energy of water required for cave tube erosion, will enhance the versatility and relevance of the presented approach to karst landscape evolution studies.

VII. ACKNOWLEDGMENTS

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