CAVE-PY: A QGIS PLUGIN TO IDENTIFY CAVE LEVELS FROM GEOSPATIALLY REFERENCED CAVE SURVEYS

CAVE-PY: VTIČNIK QGIS ZA DOLOČANJE JAMSKIH NIVOJEV NA PODLAGI GEOPROSTORSKO OPREDELJENIH RAZISKAV JAM

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Abstract UDC 004.421:912.43:551.44
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Christos Pennos & Rannveig Øvrevik Skoglund: Cave-PY: A QGIS plugin to identify cave levels from geospatially referenced cave surveys

Cave-PY is a QGIS plugin developed to identify and analyze cave levels from geospatially referenced cave survey data. Cave levels, cave tiers, or cave stories are subhorizontal passages in karst systems that develop at different elevations due to base level changes or litho-structural factors. This algorithm processes point cloud data by calculating horizontal distances between survey points based on user-defined slope thresholds and proximity radius parameters. The horizontal extent is grouped into elevation classes to identify potential cave levels. We use Stortuvhola cave located in Northern Norway, a multi-level system, where we demonstrate the plugin's ability to effectively reveal cave levels from both survey station data and complete cave survey datasets. The sensitivity tests we performed highlight the importance of appropriate parameter selection based on survey characteristics. While Cave-PY offers an efficient method for the initial extraction of cave levels, it is important that the results are validated through morphological criteria and cave survey information for correct interpretation. We believe this tool addresses a gap in the existing methodology for geospatial analysis of caves.

Keywords: cave levels, cave geometry, QGIS plugin, geospatial analysis of caves.

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Christos Pennos & Rannveig Øvrevik Skoglund: Cave-PY: vtičnik QGIS za določanje jamskih nivojev na podlagi geoprostorsko opredeljenih raziskav jam

Cave-PY je vtičnik za QGIS, ki je bil razvit za določanje in analizo jamskih nivojev na podlagi geoprostorsko opredeljenih podatkov o raziskavah jam. Jamski nivoji, jamske etaže ali jamska nadstropja so subhorizontalni prehodi v kraških sistemih, ki se razvijejo na različnih višinah zaradi sprememb nivoja podlage ali litološko-strukturnih dejavnikov. Ta algoritem obdeluje podatke z vzorčevalnih mest v oblaku tako, da izračuna vodoravne razdalje med raziskovalnimi točkami na podlagi uporabniško določenih pragov naklona in parametrov polmera bližine. Vodoravni obseg je razvrščen v višinske razrede, da se opredelijo možni jamski nivoji. Uporabili smo jamo Stortuvhola na severu Norveške, ki je večnivojski sistem, v katerem smo prikazali zmožnost vtičnika, da učinkovito razkrije jamske nivoje iz podatkov raziskovalnih postaj in celotnih podatkovnih nizov raziskav jam. Izvedeni testi občutljivosti poudarjajo pomen ustrezne izbire parametrov na podlagi značilnosti zadevne raziskave. Čeprav Cave-PY zagotavlja učinkovito metodo za začetno pridobivanje jamskih nivojev, je za pravilno interpretacijo pomembno, da so rezultati potrjeni z morfološkimi merili in informacijami o raziskavah jam. Menimo, da to orodje odpravlja vrzel v metodologiji za geoprostorsko analizo jam.

Ključne besede: jamski nivoji, geometrija jam, vtičnik QGIS, geoprostorska analiza jam.

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1. INTRODUCTION

Cave levels, cave tiers or cave storeys, are subhorizontal passages found at various elevations within karst systems due to changes on the base level (De Waele and Gutiérrez, 2022; Szczygieł, 2015; Szczygieł et al., 2020; 2019) or litho-structural conditions (Filipponi et al., 2009; Lowe and Gunn, 1997). Plan et al. (2009) define cave level as an "accumulation of phreatic galleries at strictly horizontal levels", while Audra and Palmer (2011, 2015) define cave levels as "one or more passages that are confined to a narrow vertical range". Audra and Palmer also recommend that the term cave level is only applied to passages related to an external base level, while tier or storey should be used when there is a structural or stratigraphical control on the narrow vertical passage extension. As the base level changes, cave systems adjust by incising deeper passages (i.e. vadose canyons) or filling galleries with alluvium. When the base level stays unchanged for an adequate amount of time, a new level will form.

Cave levels may correspond to external base levels (valley floor or sea level) and are thus widely applied in studies of landscape evolution, valley incision (reviewed by Calvet et al., 2024), sea level changes and tectonic uplift (Calvet et al., 2015; Piccini and Iandelli, 2010; Strasser et al., 2009). Identification of proper cave levels should be based on geomorphological investigations identifying the vadose-phreatic transition (e.g. Audra and Palmer, 2015; Calvet et al., 2024). While actual water-table caves are horizontal and developed by diffuse recharge and stable flow rates at a stationary base level, phreatic caves form loops and span a larger altitudinal interval, gently sloping towards the external base level where the upper envelope of the loops represent a floodwater table (Audra and Palmer, 2011; 2015). The loop amplitude is controlled by the hydraulic conditions related to the range of annual discharge fluctuations, and external erosion of the resurgence may influence the precision in the identification of former base level from epiphreatic caves (Calvet et al., 2024; Gabrovšek et al., 2014).

Cave passages tend to develop preferentially at specific horizons within a sequence called inception horizons (Filipponi et al., 2009; Lowe, 2000; Piccini, 2011). These horizons have physical and mineralogical properties that favor dissolution. The orientation of the horizon controls the cave tiers, which may be horizontal and thus indistinguishable from cave levels without fieldwork. Cave levels are not perfectly horizontal and may exhibit downstream variations in elevation, particularly in fluvially controlled cave systems with evident knick-points. Additionally, larger cave passages typically indicate periods of prolonged base level stability. De Waele and Gutiérrez (2022) suggest that small caves with lengths varying from 50 to 500 meters may add background noise to the data rather than contributing to a general overview. In their identification of cave levels in Totes Gebirge, Eastern Alps, Rummler et al. (2024) although discarded caves shorter than 50 m for simplification, but demonstrated that caves less than 500 m add no value to the overall analysis.

Dateable deposits within cave levels can provide valuable insights into rates of bedrock uplift and base level lowering. For example, in the Green River region in Western Kentucky, researchers documented four cave tiers/levels developed within a vertical range of 50 m over a period of 3.5 Myr, recording alternating phases of base level stability, fluvial downcutting and aggradation (Granger et al., 2001).

Cave levels are important proxies of karst systems that provide valuable information on landscape evolution. Rummler and Plan (2023) and Rummler et al. (2024) found that the distribution of cave levels on the Totes Gebirge was related to former base levels and only one broad vertical range between 1300 and 1850 m a.s.l. dominated the distribution of phreatic passages from caves ≥50 m. Szczygieł et al. (2020) in their work on the Tatra mts use cave levels as indicators of past glacier conditions. Dating cave deposits from different cave levels conclude that there is no glacial valley deepening in the area. Nehme et al. (2016) use cave levels on mt. Lebanon to identify past water table positions and reconstruct the geomorphological evolution of the area while Ballesteros et al. (2015) in their work on the Picos de Europa in Spain, use cave levels as proxies in order to infer structural controls on speleogenesis.

Cave science, and the caving community in general, have been vastly helped over the last decades by the evolution of the digital cave survey. Different software and hardware are being used by the caving community and enabled the collection of vast amounts of geospatial cave data. Here we present a Python algorithm that can be used to identify and extract cave levels from geospatial cave data. The algorithm, although simple, fills a gap in the existing methodology of the geospatial study of caves and we believe that will vastly facilitate users in handling large datasets.
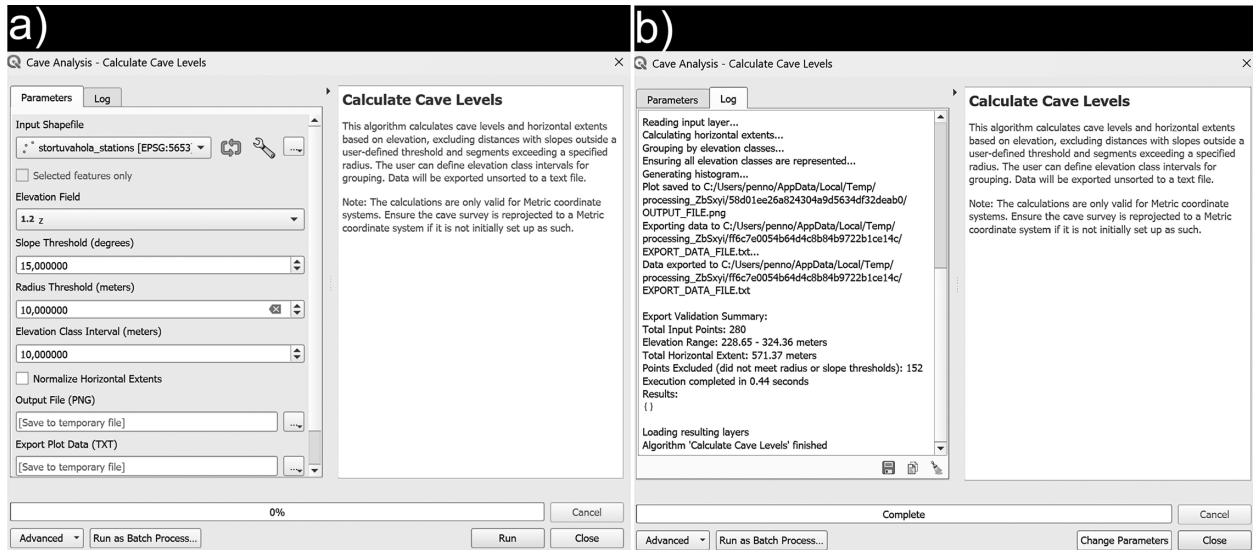
Figure 1: a) The input window of the algorithm in QGIS environment and b) the validation summary after each run.

2. THE ALGORITHM

Our Python-based algorithm is integrated within the open-source Geographic Information System (GIS) software QGIS (2024) that is widely used within both scientific and caving communities. The algorithm utilizes point cloud data, commonly exported from cave survey software (e.g., Topodroid, Sexytopo, Therion) in standard formats (txt and .shp), as input.

2.1 INPUT

The algorithm implements a user-defined input, a point cloud, based on cave survey data with an elevation attribute (i.e. survey station points). For each point, geospatial coordinates (x,y,z) from the input file (.shp or .txt) are used. The points are listed for subsequent calculations and geospatially neighboring points are compared by calculating their distance (d) and the slope (s) between them in a cartesian plane:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

$$s = \tan^{-1}\left(\frac{(z_2 - z_1)}{d}\right)$$

The calculated segments are retained for further analysis if they meet conditions below the user-defined thresh-olds both for slope and proximity radius between points. If they satisfy these conditions, the calculated horizontal distance, i.e. the level length, is assigned to the segment's midpoint elevation. If not, the segment is excluded from further analysis. Finally, all segments that meet the criteria are grouped into user-defined elevation classes for easier visual inspection.

2.2 OUTPUT

The output can be saved as a histogram plot in a png-file format as well as a text file (Figure 1a). In the run log-file, the validation summary presents statistics for each run such as the total number of input points, the total elevation range, the calculated horizontal length and the number of points/segments excluded from the analysis based on the set parameters. The horizontal length should be shorter than the survey length if only survey stations are included since the steeper survey lines should be discarded from the analysis. The output histogram can also be presented as normalized extent, which is more applicable when all survey data are included in the analysis.

3. STORTUVHOLA CAVE

Stortuvhola cave, located in Sørfold municipality in Northern Norway, is a 1484 m long cave that is developed in three different main levels. The horizontal levels of the cave are interconnected with dipping corridors exhibiting slopes that vary from 20° to 54°. The total elevation difference of the cave is 97 m and the lowest
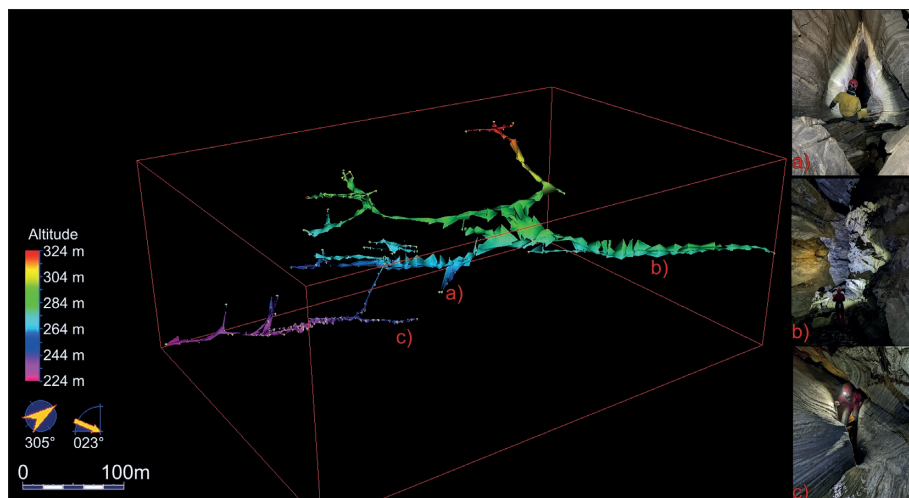
Figure 2: 3D model of Stortuvhola. Rendered using Therion software and visualized using Loch software. a, b and c inlet pictures from corresponding areas of the cave.

part of the cave hosts an active river (Figure 2). Unpublished data and observations inside the cave suggest that the cave experienced multiple base level changes related to multiple(?) cycles of glaciation that resulted in the formation of corresponding horizontal levels. For the cave survey, we used a distoX2 device and Pocketopo software on a Windows handheld device (Heeb, 2010) and followed the approach of a centerline with cross-sections perpendicular to the direction of the survey (Pennos et al., 2016). The multi-level geometry of the cave makes it an ideal candidate to test the Cave-PY algorithm.

4. SENSITIVITY TESTS

We used Stortuvhola cave to run sensitivity tests using different values for slope and radius thresholds. Using Therion (Budaj and Mudrák, 2008) we excluded the splay shots from the initial survey and the cave was exported as a georeferenced 3d.shp. The .shp was later exported through QGIS as a .txt file (although not necessary) where the elevation attribute was included for each point (Figure 3). In total 280 points (i.e. survey stations) were produced while the length of the longest survey line is 18.2 m

Threshold parameters were determined based on the initial cave survey data, with an 18.3 m search radius and a 20° slope. These values were selected because the longest survey segment is 18.2 m, and the slopes of the connecting corridors range between 20° and 55°. To account for the cave's vertical extent, a class interval of 5 m was established. As a result, 119 segments failed to meet the threshold criteria and were excluded from the analysis.

The total estimated length of the horizontal segments is 838 m. The histogram (Figure 4) reveals three distinct elevation zones with significant horizontal extents. The highest zone lies within the 325–330 m elevation range, the middle zone spans 300–260 m, and the lowest zone is between 250–230 m. The algorithm's re-

sults align with field observations, confirming its accuracy and reliability. We used these settings to set the base run for Stortuvhola.

We also tried to display the data in broader elevation classes (Figure 5a). The number of identified levels in Stortuvhola cave is retained. Still, it diminishes the resolution since closely spaced levels are no longer separated. On the contrary, when the elevation classes are too narrow, the result becomes noisy (Figure 5b). For instance, a 15 m long segment with a slope of 20° will have a vertical extension of 5 m, and the horizontal extent will be assigned to the class holding the segment's midpoint elevation, which may seem arbitrary since it extends over several classes.

When the radius threshold is low (Figure 6a), only shorter survey segments are included in the analysis. Hence the total horizontal extent becomes low and not representative of the cave. For Stortuvhola cave, larger passages at the mid-level, where the survey station intervals are longer than 5 m, are excluded from the analysis. Accordingly, the major peak from the base run (Figure 4) is reduced and is divided into two parts. Furthermore, the narrow winding passages at the lowest level, where survey lines are short and the survey stations closely spaced, dominate in this histogram. Choosing a radius
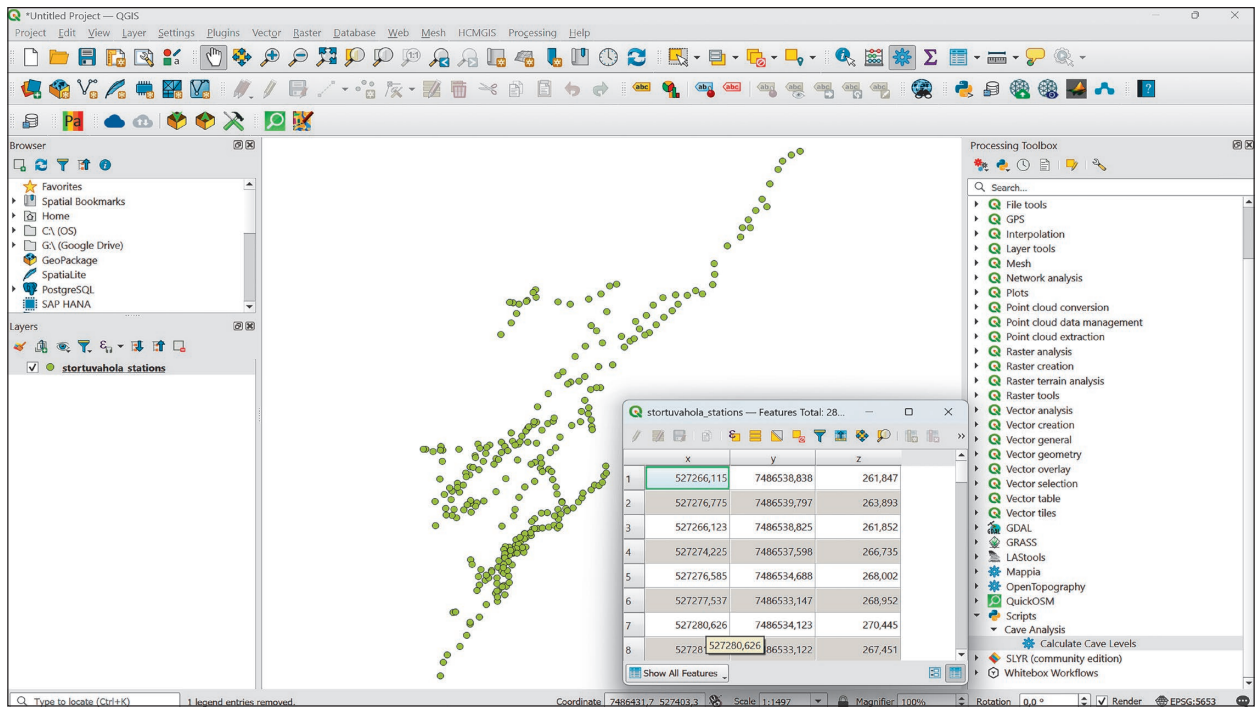
Figure 3: Survey points of Stortuvhola on QGIS. The attribute table shows the data for each point (i.e. xyz values).
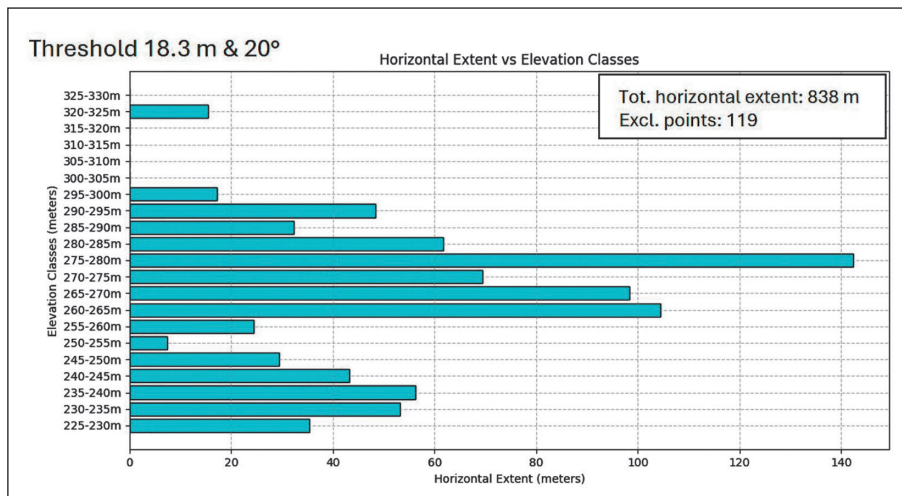

Figure 4: Output from Cave-PY analysis based on survey stations from Stortuvhola cave displaying the horizontal extent of cave corridors with a radius threshold of 18.3 m and a slope threshold of 20° in 5 m vertical interval classes. 119 out of 280 points were excluded from the analysis. The total horizontal extent is 838 m.
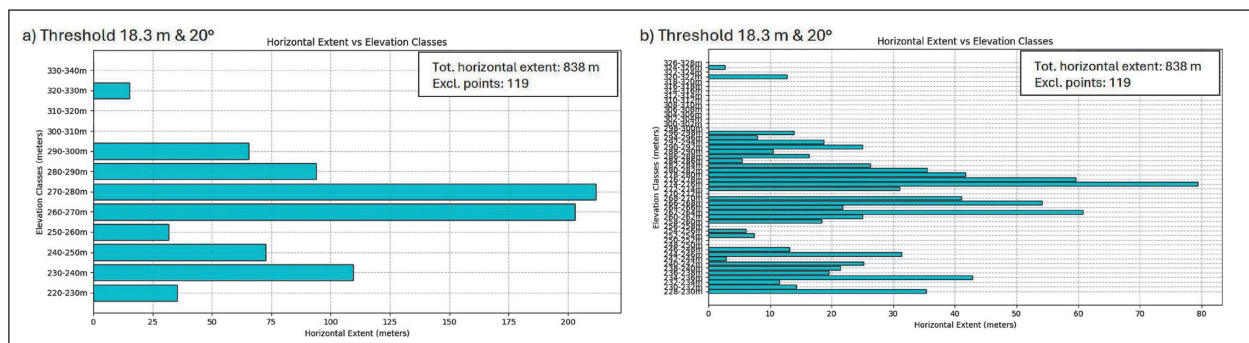

Figure 5: Output from Cave-PY analysis based on survey stations from Stortuvhola cave displaying the same analysis as in Figure 4 in 10 m (a) and 2 m (b) elevation classes.

threshold much larger than the longest survey segment (Figure 6b) introduces segments in the analysis that do not reflect existing cave corridors. In this case, cave sections with several side passages may be overrepresented in the analysis.

Defining a low slope threshold means that most of the sloping passages will be excluded and the analysis runs on a small selection of survey stations (Figure 7a). In contrast, a high slope threshold allows most of the stations to be included in the analysis (Figure 7b). In the case of Stortuvhola cave, the overall shape of the histogram stays the same with some minor changes in the dominant classes.

Cave-PY analysis can be implemented on the complete cave survey data, including all cross-section data. For the case of our data, it consists of 5580 points. Running the analysis with the same thresholds as the base run (18.3 m and 20°) excludes 3741 points from the analysis giving a total horizontal extent of 2425 m. Analyzing the full point cloud from the survey, the user should understand that the length of the cave is overestimated by the algorithm thus the total length for each class is
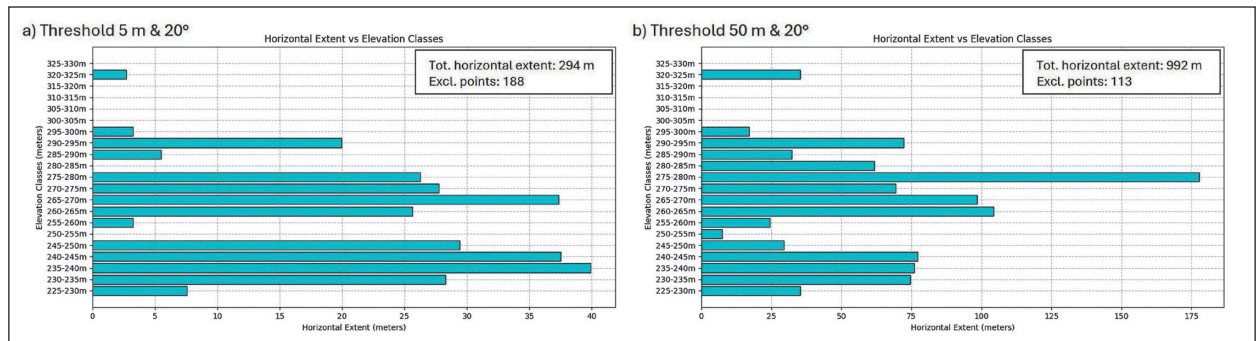

Figure 6: Output from Cave-PY analysis based on survey stations from Stortuvhola cave displaying the influence of changing the radius threshold. In a) the radius threshold is 5 m, and in b) 50 m. The other parameters are the same as in Figure 4.
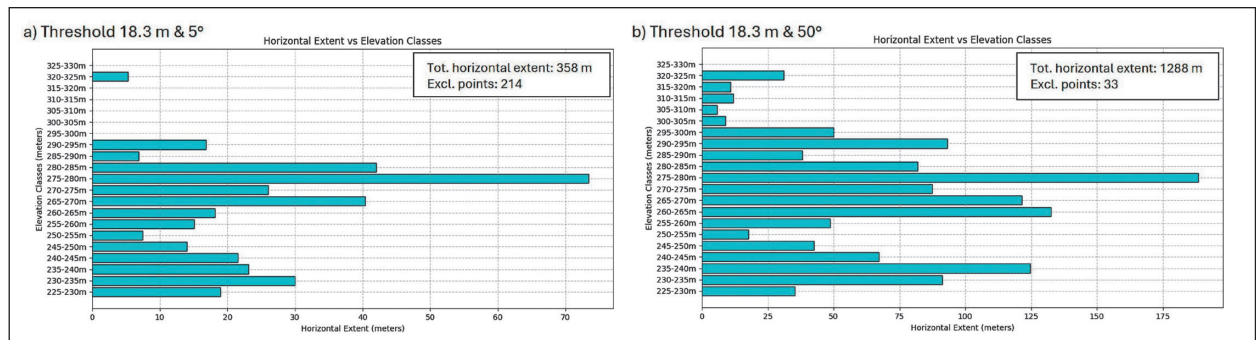

Figure 7: Output from Cave-PY analysis based on survey stations from Stortuvhola cave displaying the effect of changing the slope threshold. In a) the slope threshold is 5°, and in b) 50°. The other parameters are the same as in Figure 4.
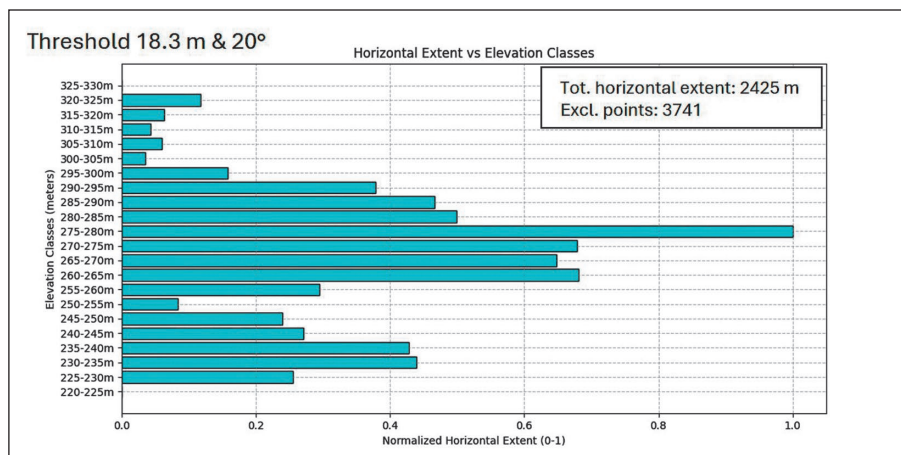

Figure 8: Output from Cave-PY analysis based on all survey data from Stortuvhola cave, including cross-sections. 3741 out of 5580 points were excluded from the analysis. The horizontal extent is shown as normalized values since the estimated length is not comparable to the length of cave passages (1484 m).

not accurate to the real world to the cave passage length. For this dataset type, the histogram should be used with a normalized horizontal extent (Figure 8) and the output should be treated as qualitative. The overall pattern of the histogram is the same, showing three distinct levels, where the major level is broader without subpeaks.

5. DISCUSSION

The sensitivity tests have demonstrated that the Cave-PY algorithm can handle both point clouds including all cave survey data and datasets with survey stations exclusively. For point clouds comprising survey stations only, the dataset should preferably consist of a systematic survey from the entrance to the most distant part of the cave. In linear cave systems, this is achievable. In branch-work and network caves, there will be consecutive points in the list that do not represent survey lines due to closed loops and blocked or dead-end passages. However, most of these segments can be excluded from the analysis based on the threshold criteria. Threshold values should be defined based on the input data, considering survey strategy, e.g. length of survey segments, and location of survey stations.

Although the plugin can produce meaningful results, it is crucial to understand what the cave levels represent. It is of great importance to use a reliable dataset (Lønøy et al., 2021; Lønøy et al., 2020) and to prepare the data before running the algorithm to extract useful results.

Cave-PY provides a quick way to extract the extent of horizontal cave passages and identify potential cave levels, storeys or tiers. Further interpretation should be based on morphological criteria and information from the cave survey.

CODE AVAILABILITY

The code can be downloaded from the github repository using this link (https://github.com/cpenpen/cave-PY) or by direct request to the authors.

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