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Integrated 3D Laser Scanning, LiDAR and GIS Documentation of the Ravne Underground Complex (Bosnia and Herzegovina): Spatial Architecture of Six Tunnel Systems

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Abstract

The Ravne Underground Complex near Visoko consists of six tunnel systems (Ravne 1 - 6) cut into Quaternary conglomerate. Until 2026 they had never been surveyed in one coordinate frame. In 2026 a GNSS control network of 15 control points and four check points was established, the surface was flown with a UAV LiDAR system (DJI Matrice 350 RTK with Zenmuse L2), and the accessible underground passages were scanned from about 719 terrestrial laser scanner stations (Trimble X7 and TX8). The scans were registered in Trimble RealWorks, tied to the control network through the UAV LiDAR cloud in MGI/Balkans zone 6 (EPSG:31276) with heights in BH_VRS1971.5, drafted in Autodesk Civil 3D and organized in an ArcGIS Pro database. The surveyed accessible length is 2452.7 m, with 3379.6 m^2 of floor area and about 5490 m^3 of open volume, of which about 25 m^3 (Ravne 2) is estimated. Ravne 1 accounts for 70% of that length. Mean corridor width is 1.38 m and mean clear height 1.62 m. All six systems lie within a 5.57 m elevation band (469.93 - 475.50 m a.s.l.), and mean floor gradients range from 0.94% to 2.0%. Footprint areas re-measured independently from the georeferenced survey drawings agree with the reported values to within 0.5% - 2.7%. At independent check points the LiDAR heights agree with GNSS to 0.054 m (RMSE), and the tunnel clouds fit the LiDAR surface with cloud-to-cloud errors of 0.031 - 0.035 m. About 514 m of water-filled passages, tape-measured in 2012-2014, and low passages of unmeasured length remain unscanned. With the water-filled passages the documented subtotal is about 2.97 km. The dataset is a measured spatial baseline for further excavation, monitoring and interdisciplinary work. It does not, by itself, address the origin or age of the tunnels.

Keywords

Terrestrial Laser Scanning, UAV LiDAR, GNSS Control Network, GIS, Underground Heritage Documentation, Tunnel Geometry, Ravne, Visoko, Bosnia and Herzegovina

1. Introduction

Underground spaces are hard to measure. They are dark, narrow, often wet, and they have no line of sight to satellites. Tape-and-compass surveys accumulate error along every leg. They also record the axis of a passage, not its shape. Terrestrial laser scanning (TLS) changed this. A scanner records millions of points per station, and overlapping stations can be registered into one continuous model of walls, floor and ceiling [1]. TLS is now standard in tunnel construction [2] [3], cave mapping [4] [5] and archaeological recording [6] [7].

The Ravne Underground Complex near Visoko, Bosnia and Herzegovina, has been excavated and studied since 2005. Earlier work covered its stratigraphy, finds and dating [8] [9], its dry-stone walls [10], the backfilling of passages [11] and its geology and microclimate [12]. Those studies used local plans of individual tunnels. None placed all six tunnel systems in a single, georeferenced frame. Total length, cross-section, elevation and mutual position were therefore known only roughly. Earlier summaries gave the network as "over three kilometres" without a measured breakdown [13].

In August 2026, the Foundation commissioned GeoGIS studio d.o.o. (Sarajevo) to survey the complex. The survey combined a GNSS control network, UAV LiDAR, TLS of all accessible passages, 360˚ imagery, CAD drafting and a GIS database [14].

This paper reports the geodetic and three-dimensional results. It has four aims:

1) Describe the survey workflow and its reference frame.

2) Report length, area, volume, cross-section and floor elevation for each of the six systems.

3) Describe their planimetric form, orientation and spatial relationships.

4) State what the survey did not cover and what that means for the totals.

The paper is descriptive and metric. It does not re-examine the archaeological record, and it draws no conclusion about how or when the tunnels formed.

2. Study Area and Previous Work

The complex lies in the Ravne locality, cadastral municipality Kraljevac, Visoko, about 43˚59'N, 18˚09'E [9]. The ground surface across the survey area ranges from 456 to 500 m a.s.l. Entrances open at the foot of a forested slope that rises to the east and south-east (**Figure 1**). Ravne 2, 3, 4 and 6 open within Park Ravne 2 [15].

The passages are developed in Quaternary conglomerate. The conglomerate overlies marl and sandstone. Its clasts include quartz, quartzite, chert, sandstone, shale, schist and basalt in a calcite-bearing matrix [12]. Groundwater circulates

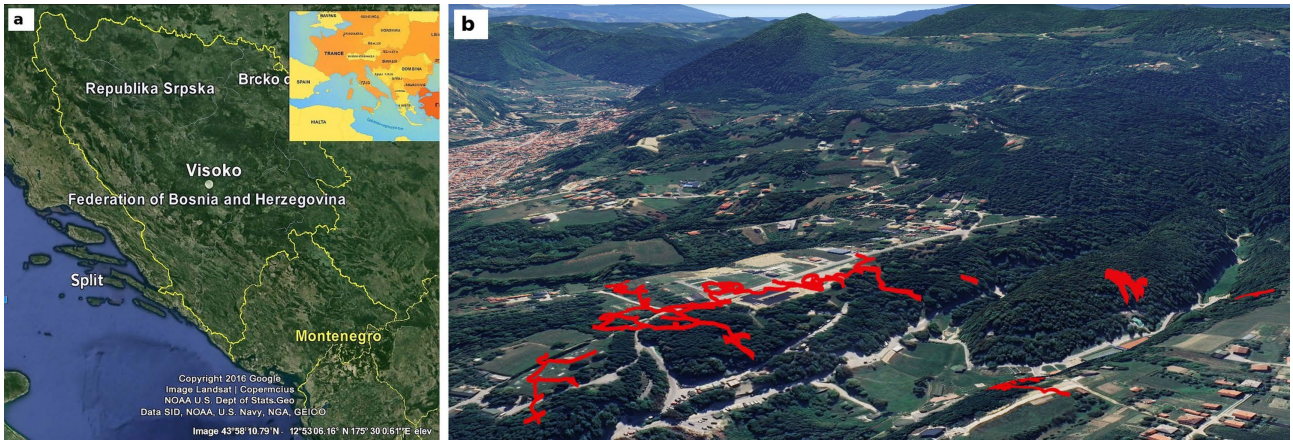

Figure 1. Location of the Ravne Underground Complex. (a) Visoko in central Bosnia and Herzegovina; base map adapted from [16], CC BY 4.0. (b) Oblique view of the Ravne locality with the surveyed tunnel systems projected in red. Source: GeoGIS studio [17]; base imagery © Google Earth.

through parts of the system. Some passages hold standing or flowing water year-round, so we could not scan them (Section 5.2).

Ravne 1 is by far the largest system. Ravne 2 - 6 are separate tunnel sections with their own entrances. Their archaeology is summarized elsewhere [8] [16]. Previous plans were drawn for individual sections, including the 2025 excavation plan of Ravne 6 [9]. Those plans were not on a common datum, so they could not be combined. Earlier published descriptions give approximate lengths only.

3. Materials and Methods

The fieldwork and primary processing were carried out by GeoGIS studio d.o.o., Sarajevo (project 3.1.8.-171/26). The work ran in five linked stages: control network, UAV LiDAR, TLS, 360˚ imagery, and processing into CAD and GIS products [17]. **Table 1** lists the equipment.

Table 1. Equipment and software.

Stage	Equipment/software	Role
Control network	Tersus Oscar and Luka GNSS receivers, 2 m pole	15 control and 4 check points; network RTK (FBiHPOS), 10 epochs, three cycles
Surface survey	DJI Matrice 350 RTK with DJI Zenmuse L2 LiDAR	Point cloud and orthophoto of the whole complex
LiDAR processing	DJI Terra	Point cloud, georeferencing, orthophoto
Underground scanning	Trimble X7; Trimble TX8	About 719 scanner stations
Registration	Trimble RealWorks	Cloud-to-cloud registration; tie to UAV LiDAR
Data exchange and viewing	ASTM E57 format; Autodesk ReCap	Point cloud delivery
Drafting	Autodesk Civil 3D	Plans, axes, stationing, metrics
GIS	Esri ArcGIS Pro; custom “GIS Tuneli Ravne” application	Attribute database, layers
Visual record	Insta360 camera; 3DVista Virtual Tour Pro	360˚ panoramas and virtual tour

3.1. Control Network

Fifteen control points (GG1 - GG15) were set and paint-marked so they were visible from the air. Four further points, T1 - T4, were added as check points. We observed each point with Tersus Oscar and Luka receivers in network RTK mode, using corrections from FBiHPOS, the permanent GNSS station network of the Federal Administration for Geodetic and Real Property Affairs. The antenna stood on a 2 m pole, leveled over the mark, and each fix averaged 10 epochs in the receiver's CONTROL H + V mode. The points were observed in three separate cycles, and the final coordinates are the means. The manufacturer quotes RTK accuracy of 8 mm + 1 ppm horizontal and 15 mm + 1 ppm vertical. Achieved GNSS RMS values are 0.025 - 0.040 m (**Appendix A**). Coordinates are in the state coordinate system, MGI/Balkans zone 6 (EPSG:31276), on the Bessel 1841 ellipsoid. We transformed GNSS coordinates using a seven-parameter similarity transformation adopted from the Visoko municipal survey office (**Appendix A**). Heights are in BH_VRS1971.5, the inherited vertical reference system of the Federation of Bosnia and Herzegovina. It derives from the second high-accuracy leveling and refers to mean sea level at five Adriatic tide gauges, epoch 1971.5 [18]. The geoid or quasigeoid model used to convert ellipsoidal heights to BH_VRS1971.5 is not recorded in the survey documentation [19]. All elevations in this paper, given as m a.s.l., refer to BH_VRS1971.5. Point elevations range from 456.05 m (GG11) to 500.18 m (GG14) (**Figure 2**).

3.2. UAV LiDAR

We flew the entire complex with a DJI Zenmuse L2 sensor on a DJI Matrice 350 RTK. Flight lines were planned for continuous coverage of the project area without gaps between zones. The data were processed in DJI Terra into a point cloud and an orthophoto. Coverage gaps, strip overlap and georeferencing were checked against the control points, and corrections were applied before delivery. The planned flight height was 60 m, with 70% forward and 30% side overlap, and RTK corrections from FBiHPOS were applied in flight. The LiDAR cloud was fitted in Trimble RealWorks to eight control points; four further control points and T1 - T4 served as independent checks (**Appendix A**). Flight speed and point density are not recorded [19]. The surface products give the context for the underground survey (**Figure 3**).

3.3. Terrestrial Laser Scanning

All accessible passages of Ravne 1 - 6 were scanned with a Trimble X7 and a Trimble TX8. Two teams of two engineers worked in parallel. The X7 is a self-levelling, self-calibrating scanner with field registration. At key locations it was set to four-minute scans with colour capture. The TX8 is a time-of-flight scanner. The manufacturer quotes up to 1 million points per second and a standard range of 120 m. Scanning of each tunnel began at its entrance, where the scans overlap the ground surface covered by the UAV LiDAR (Section 3.4). Stations then

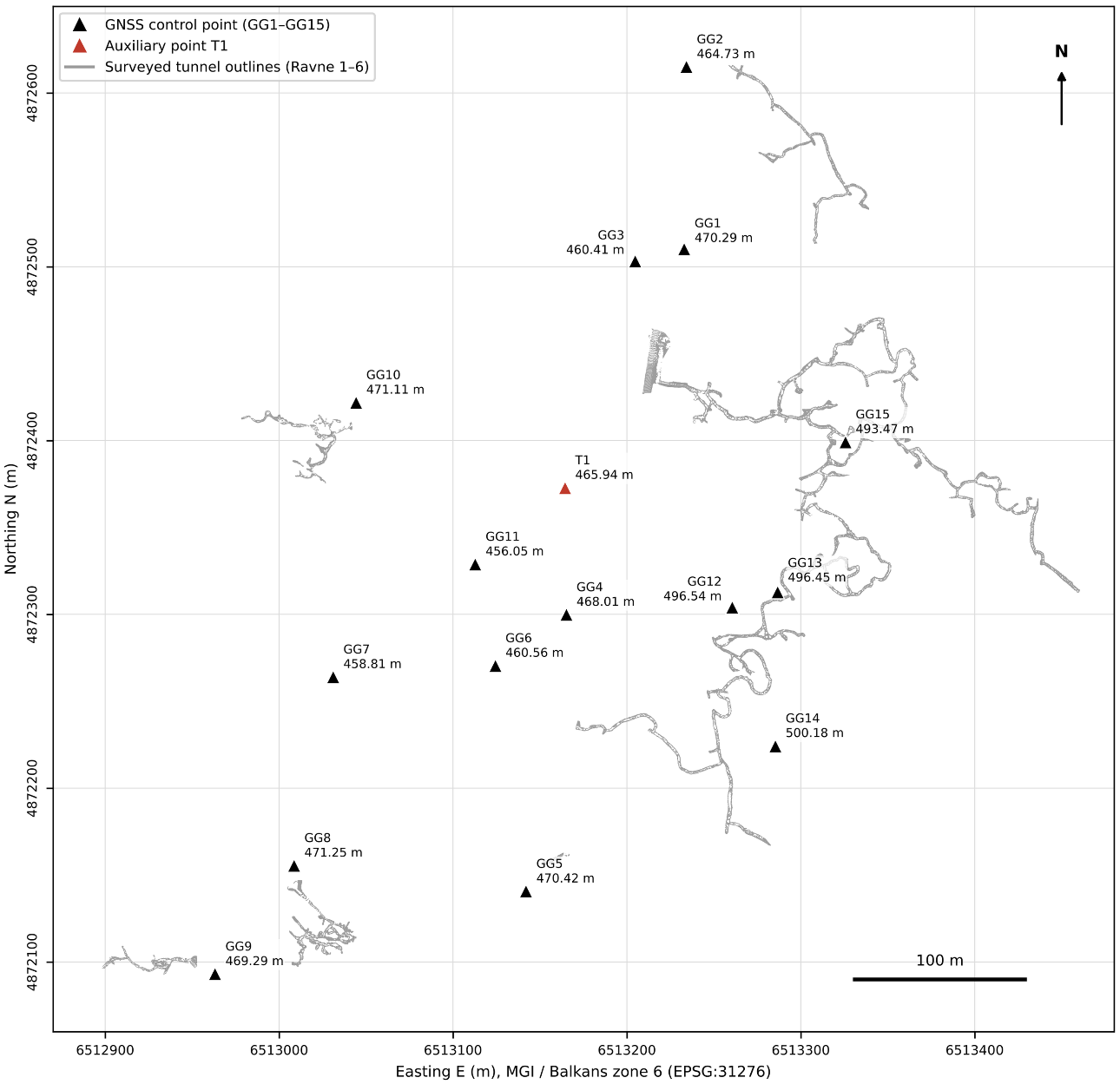

Figure 2. GNSS control network of the Ravne Complex: fifteen control points (GG1 - GG15) and check point T1 (T2 - T4 not shown), with heights in m a.s.l. Grey lines show the surveyed tunnel outlines for reference. Coordinates in MGI/Balkans zone 6 (EPSG:31276). Data: GeoGIS studio [17].

followed the passage at spacings chosen to keep adjacent scans overlapping. Stations were added at bends, junctions, galleries and side passages. **Table 2** gives the station count per system.

3.4. Registration and Georeferencing

Scans were registered in Trimble RealWorks, one project per tunnel. Registration was cloud-to-cloud (targetless), using walls, floors and ceilings shared by neighboring stations. This is the same principle as iterative closest-point alignment [20].

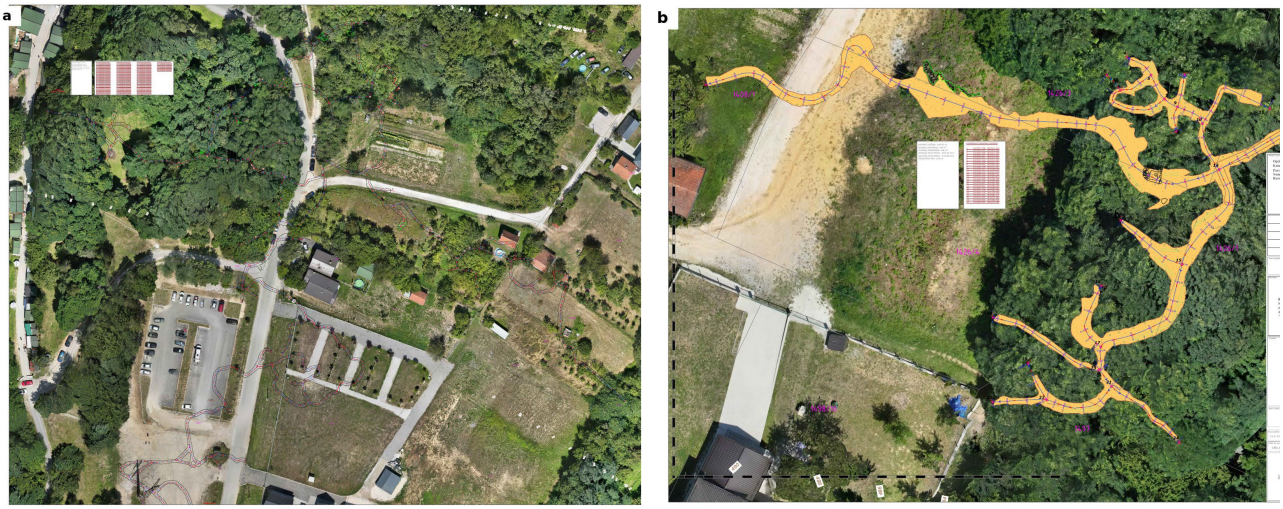

Figure 3. UAV orthophoto with the surveyed tunnel footprints overlaid. (a) Ravne 1 sector; (b) Ravne 3, with the footprint shown in orange and the corridor axis in blue. Source: GeoGIS studio [17], survey sheets 4.1.1 and 4.3.1.

Table 2. Scanner stations per system.

System	Stations	Scanner	Stations per 100 m surveyed
Ravne 1	≈550	X7, TX8	32
Ravne 2	8	TX8	58
Ravne 3	59	X7, TX8	28
Ravne 4	19	X7	23
Ravne 5	47	X7, TX8	19
Ravne 6	36	X7, TX8	19
Total	**≈719**		**29**

Note: stations per 100 m are computed from **Table 3** lengths.

We linked each scan to the previous one along the passage. To limit drift along long passages, extra links were made wherever a side passage or loop returned to an already-scanned area. The result is a network of links, not a single chain. The registered cloud of each tunnel was then fitted separately to the UAV LiDAR cloud over the ground around its entrance. The LiDAR cloud had itself been fitted to the control points. The position and orientation of each tunnel cloud therefore rest on the LiDAR surface around its entrance. Ravne 1 has two entrance-exit openings, which provided an additional geometric check for registration [19]. Registration statistics are given in **Appendix A**. Clouds were exported in the ASTM E57 format [21] and reviewed in Autodesk ReCap.

3.5. Drafting and Metrics

The registered clouds were drafted in Autodesk Civil 3D. The drawings show tunnel walls, plan footprint, corridor axes with chainage, and numbered axis-intersection points with coordinates. A total of 175 such points were listed: 98 for

Ravne 1, 2 for Ravne 2, 24 for Ravne 3, 10 for Ravne 4, 15 for Ravne 5 and 26 for Ravne 6. For each system the surveyor reported total length, plan area, volume, lowest and highest floor elevation, and mean floor gradient. Volumes were computed in Civil 3D as the difference between two surface models built from the point cloud, one of the ceiling and one of the floor [19]. In a surface-to-surface calculation, occluded parts of the floor or ceiling are bridged by triangles between the nearest measured points, and each volume ends where the scanned surfaces end, at the last scanned section of a passage. Backfilled, flooded and unscanned sections are therefore excluded. The floor model includes points on the gentle lower slopes toward the walls, recorded so that it represents the full lower cross-section [19]. Two values were missing for Ravne 2: gradient and volume. The floor extrema of Ravne 2 do not lie at its ends: the lowest floor point is at the entrance and the highest about 7 m inside. A range-based value would therefore misstate the gradient. We give instead the signed regression gradient from the floor points, about 0.8% [22]. The volume is estimated as plan area times the mean clear height of the other five systems (1.62 m). Its bounds use the lowest (1.36 m) and highest (1.94 m) of those heights. The total volume includes this estimate.

The mean floor gradient is the slope of the straight line joining the lowest and highest points of the floor line on a longitudinal profile cut vertically along the main axis of each system [19]. It is an unsigned global value for one profile; side branches are not aggregated into it. Signed, length-weighted gradients computed from the floor point lists for all branches are reported in a companion paper [22]. They are positive away from the entrance in all six systems, at 0.23% - 2.71%.

Two cross-sectional parameters are derived for this paper:

- Mean corridor width = plan area/length.
- Mean clear height = volume/plan area.

These are averages over each system. They do not replace measured cross-sections.

3.6. GIS and Visual Record

The Civil 3D data were converted into an Esri ArcGIS Pro geodatabase, with geometry and attributes checked in conversion. Features from all six tunnels share one schema, coded by tunnel. Recorded elements such as dry-stone walls carry their own attributes. A purpose-built application, "GIS Tuneli Ravne", gives layer control, measurement and export. Its database is designed to take future finds and newly opened sections. In parallel, 360˚ panoramas were taken through Ravne 1 - 6 with an Insta360 camera and linked into a virtual tour in 3DVista.

3.7. Independent Checks Made for This Paper

The survey drawings were delivered as vector PDF sheets. We extracted the line work and georeferenced it by matching the drawn axis vertices to the 175 listed axis-intersection coordinates. The sheet scale was fixed (1:100 to 1:250), and only a translation was fitted. North-up orientation was confirmed by the match. The georeferenced drawings were then used for four checks:

1) Plan footprints of Ravne 2 - 6 were rasterized at 5 cm and their areas compared with the reported values.

2) A planimetric trend and an elongation ratio were computed for each system by principal-component analysis of wall outlines resampled at 0.2 m.

3) Minimum distances between systems were measured from the wall outlines.

4) Control-point heights were compared with tunnel floor elevations where a control point lies on or beside a tunnel.

4. Results

4.1. The Complex in One Frame

All six systems now sit in one coordinate frame (Figure 4). The surveyed passages

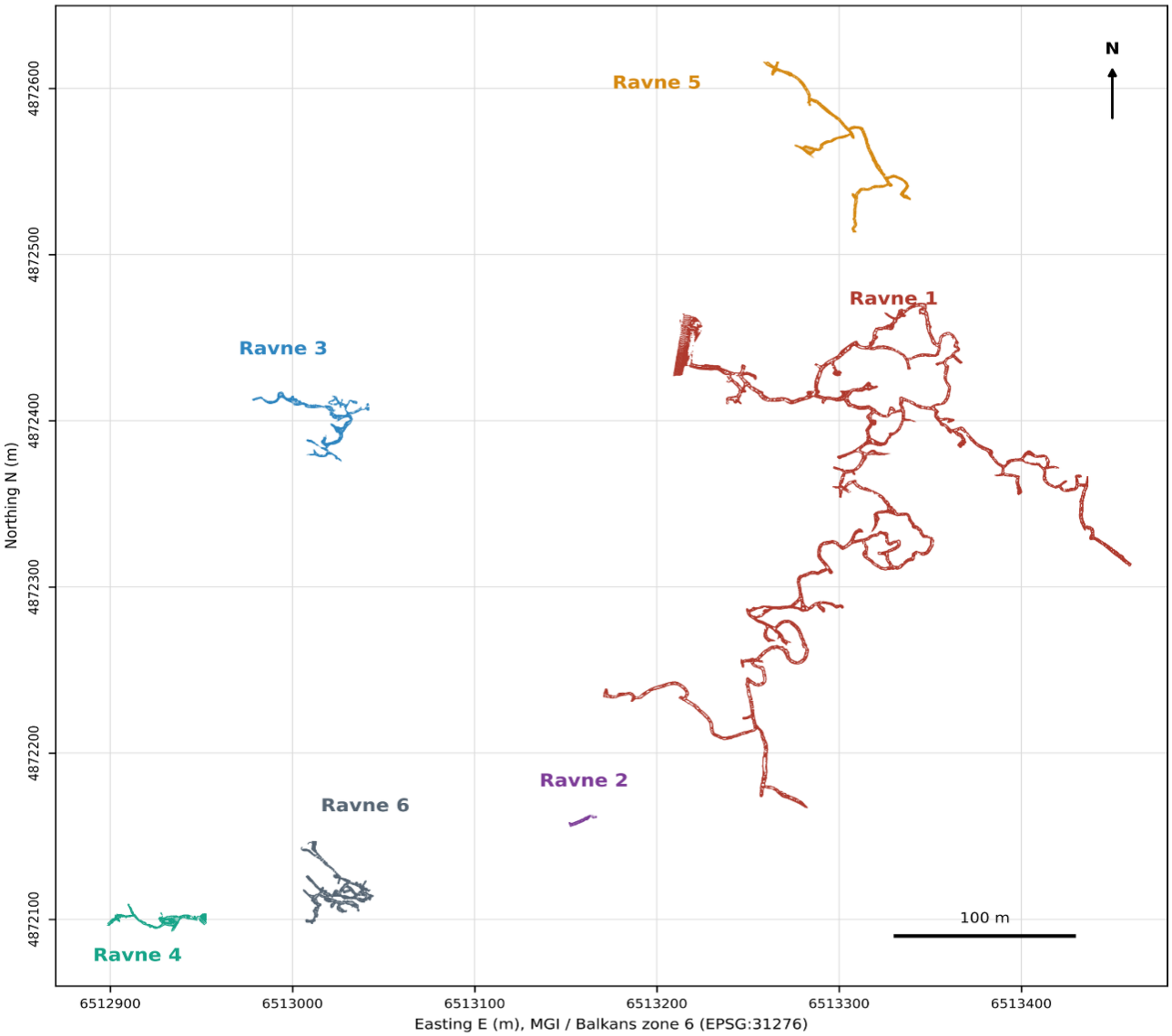

Figure 4. Integrated plan of the Ravne Underground Complex: surveyed walls of all six systems in MGI/Balkans zone 6 (EPSG:31276). Filled areas show plan footprints where the survey drawings provide them (Ravne 2 - 6). Total surveyed accessible length is 2452.7 m. Drawn from the georeferenced GeoGIS [17] survey sheets.

occupy an area about 562 m east-west by 523 m north-south. Ravne 1 fills the eastern half of that area. Ravne 5 lies to its north. Ravne 2, 4, and 6 lie to the southwest, and Ravne 3 lies to the west.

4.2. Length, Area, Volume and Cross-Section

The surveyed accessible length is 2452.7 m (Table 3). Ravne 1 contributes 1706.5 m, or 70% of the total, and 72% of the volume. The other five systems range from 13.9 m (Ravne 2) to 251.3 m (Ravne 5).

Table 3. Metric summary of the six systems. Length, area, volume and gradients are from the GeoGIS [17] survey sheets unless marked. Floor elevations are the lowest and highest interior floor points in the GeoGIS point lists, portal approaches excluded [22]; the sheet summaries give lower maxima for Ravne 2, 3, 5 and 6. Elevations refer to BH_VRS1971.5. Mean width and mean clear height are derived in this paper (Section 3.5).

System	Length (m)	Plan area (m^2)	Volume (m^3)	Mean width (m)	Mean clear height (m)	Floor elevation (m a.s.l.)	Mean gradient	Axis points
Ravne 1	1706.52	2,465	3,958	1.44	1.61	471.42 - 475.50	1.0%	98
Ravne 2	13.9	15.34	≈25 (21 - 30)[a]	1.10	—	470.44 - 470.90	≈0.8%[a]	2
Ravne 3	208.90	246	406	1.18	1.65	469.93 - 471.44	0.94%	24
Ravne 4	84.4	93.8	152	1.11	1.62	470.45 - 472.00	1.9%	10
Ravne 5	251.3	325	629	1.29	1.94	470.11 - 472.49	1.4%	15
Ravne 6	187.7	234.5	320	1.25	1.36	471.33 - 473.50	2.0%	26
Total	**2452.7**	**3379.6**	**≈5490**	**1.38**	**1.62[b]**	**469.93 - 475.50**		**175**

[a]Estimated in this paper (Section 3.5). [b]Ravne 1 and 3 - 6 only.

The passages are narrow and of walking height or a little less. System means range from 1.10 to 1.44 m in width and from 1.36 to 1.94 m in clear height. Ravne 5 has the tallest mean section and Ravne 6 the lowest. These are averages. The point clouds show local widenings at junctions and chambers, and low, narrow sections elsewhere (Sections 4.3 and 4.4).

4.3. Ravne 1

Ravne 1 is a dense, branching network (Figure 5 and Figure 6). Its main axis is stationed to 6+37.60, a chainage of 637.6 m. The other 1069 m are side passages, loops and dead ends. Ninety-eight axis-intersection points were listed for it. The plan has no single dominant direction. Its principal-component elongation is 1.1, the lowest of the six systems (Table 4). Two features stand out. Several closed loops occur in the central and southern parts. A long branch also runs south-east for about 150 m in plan from the central junction zone. The entrance zone in the north-west appears as a hatched structure on the survey drawings.

4.4. Planimetric Form and Orientation

The six systems differ strongly in form (Figure 7, Table 4). Ravne 2, 4 and 5 are

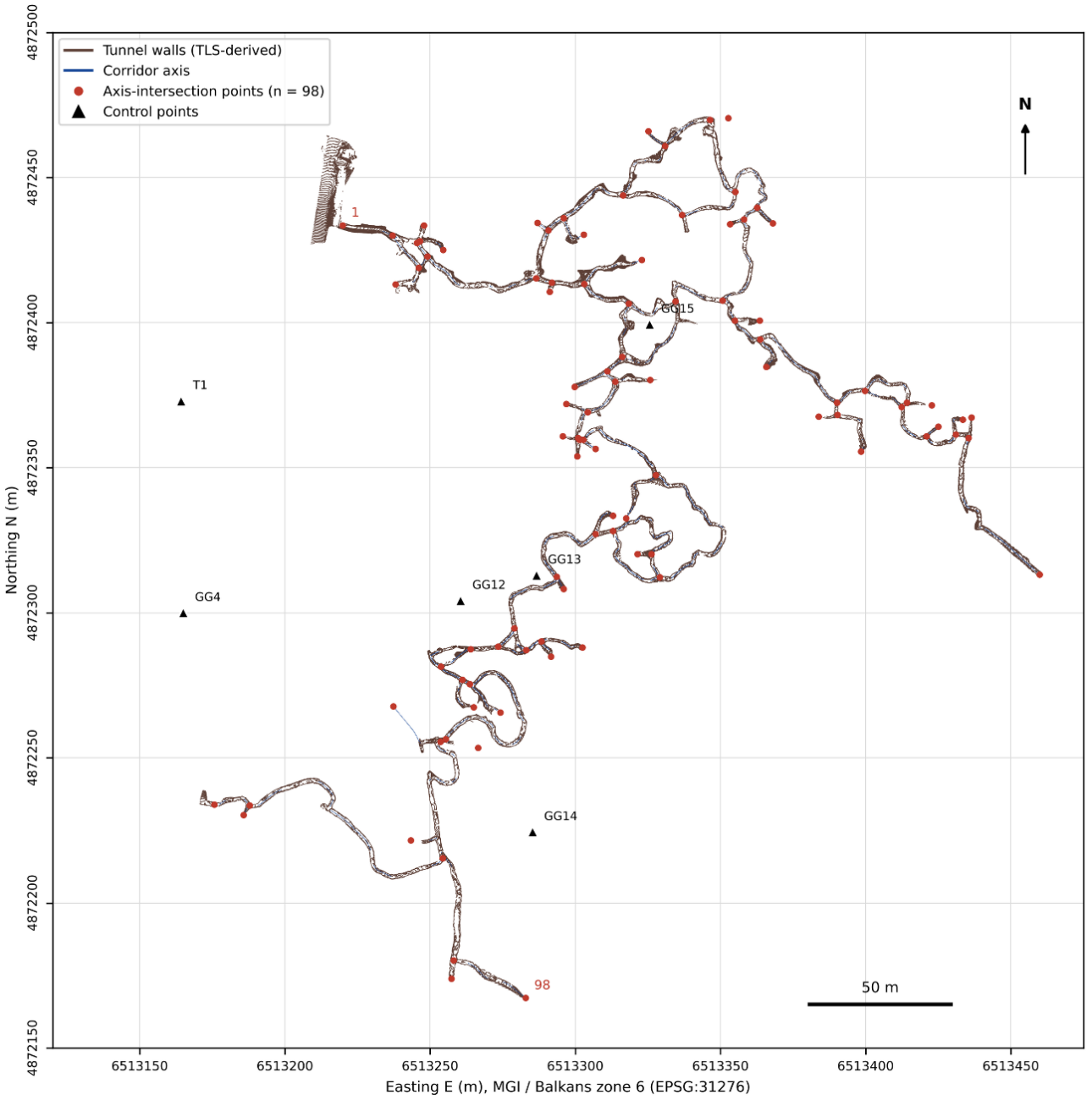

Figure 5. Geodetic plan of Ravne 1: TLS-derived walls, corridor axis and the 98 axis-intersection points (first and last numbered). Black triangles are nearby control points. Drawn from the georeferenced GeoGIS [17] sheets 4.1.1.

elongated, with elongation ratios of 2.7 to 5.1. Ravne 1, 3 and 6 are compact, branching networks with ratios of 1.1 to 1.4.

Trend values are only meaningful for the elongated systems. Ravne 4 runs almost due east-west (91˚). Ravne 5 runs north-west to south-east (143˚). For Ravne 1, 3 and 6 the trend describes the overall spread of a branching network, not a corridor direction.

Ravne 4 is a single corridor with a timber-lined entrance section and a fork (**Figure 8**). Passages beyond the first fork were too low to scan. Ravne 6 is a short



Figure 6. Plan-view rendering of the Ravne 1 TLS point cloud (≈550 stations, Trimble X7/TX8). The rendering shows wall texture, branching geometry, loops and dead-end passages. Rendering prepared by the Foundation from the GeoGIS [17] point cloud; not to scale.

Table 4. Planimetric form. Trend is the azimuth of the major principal axis of the wall outline, measured clockwise from grid north (0 - 180˚). Extent is measured along the major and minor axes.

System	Trend (˚)	Extent, major × minor (m)	Elongation	Nearest system (gap, m)
Ravne 1	19	310 × 282	1.1	Ravne 5 (51)
Ravne 2	67	16 × 3	5.1	Ravne 1 (71)
Ravne 3	124	61 × 44	1.4	Ravne 1 (168)
Ravne 4	91	54 × 16	3.4	Ravne 6 (55)
Ravne 5	143	115 × 42	2.7	Ravne 1 (51)
Ravne 6	139	49 × 41	1.2	Ravne 4 (55)

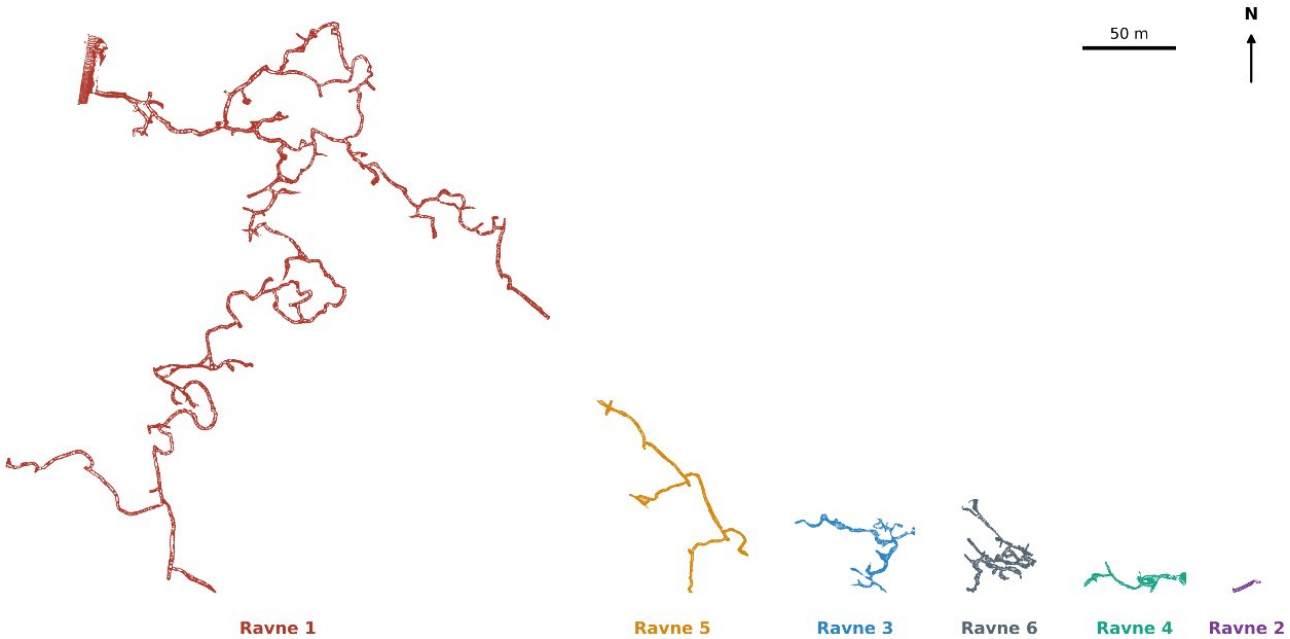

Figure 7. The six systems at the same scale, ordered by size. Walls drawn from the georeferenced GeoGIS [17] survey sheets; filled areas are plan footprints.



Figure 8. Plan-view rendering of the Ravne 4 TLS point cloud (19 stations, Trimble X7). The timber-supported entrance section is at the right, and the main corridor and first fork are to the left. Rendering prepared by the Foundation from the GeoGIS [17] point cloud; not to scale.

entrance passage that opens into a tight cluster of intersecting corridors, with 26 axis-intersection points in about 50 × 40 m (Figure 9).

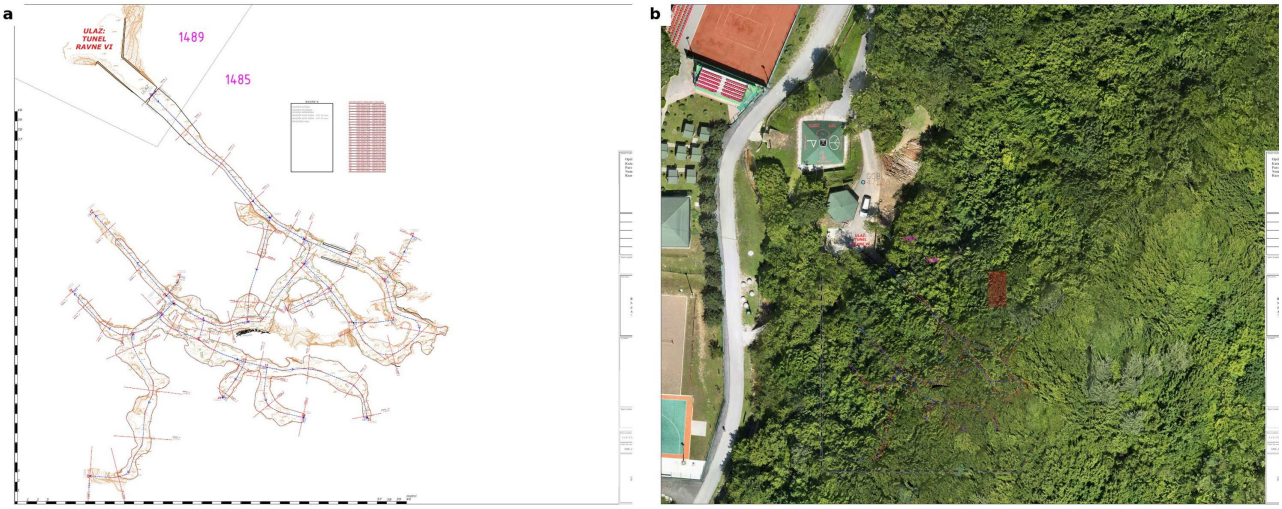

Figure 9. Ravne 6. (a) Survey plan with walls, corridor axes, chainage and axis-intersection points. (b) The same area on the UAV orthophoto at 1:250. Source: GeoGIS studio [17], sheets 4.6.2 and 4.6.3.

4.5. Floor Elevations and Gradients

All surveyed floors lie between 469.93 and 475.50 m a.s.l., a band of only 5.57 m (Figure 10). Five of the six systems lie within 3.6 m of each other, between 469.93 and 473.50 m. Ravne 1 spans the widest range (4.1 m) and reaches the highest floor level. Mean gradients are gentle, from 0.94% (Ravne 3) to 2.0% (Ravne 6) (GeoGIS profile values; Section 3.5). Within any one system, the floor varies by at most 4.1 m.

The tunnels run beneath rising ground. Control points GG13 (496.45 m) and GG15 (493.47 m) stand within 4 m in plan of Ravne 1 passages. Point GG12

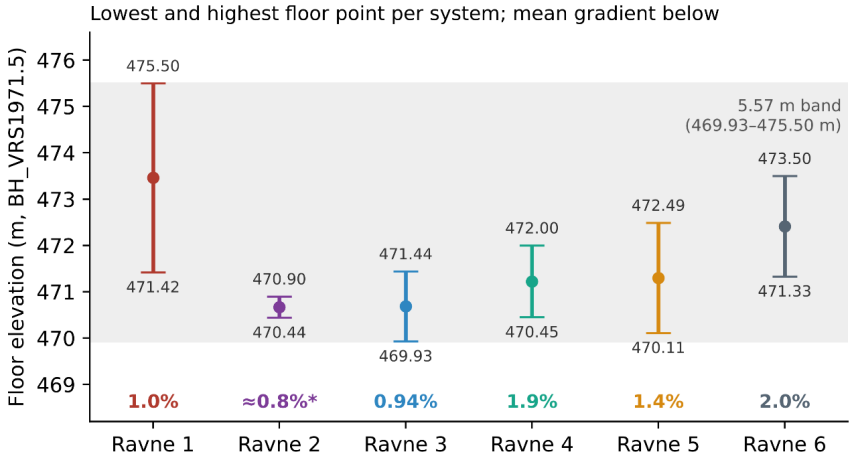

Figure 10. Lowest and highest floor point of each system in the GeoGIS point lists (whiskers, with the mid-point marked) and mean floor gradient (below). The shaded band marks the common range, 469.93 - 475.50 m a.s.l. (BH_VRS1971.5). Ravne 2 gradient (*) is estimated in this paper from the floor points (Section 3.5).

(496.54 m) stands 16 m away. The Ravne 1 floor there is at 471.5 - 475.5 m. The ground above these passages is therefore about 18 - 25 m higher than the floor. This is an estimate from three control points, not a measured overburden profile.

4.6. Spatial Relationships between the Systems

No two systems connect in the surveyed data. The smallest gaps are between Ravne 1 and Ravne 5 (51 m) and between Ravne 4 and Ravne 6 (55 m). Ravne 2 lies 71 m from Ravne 1. Ravne 3 is the most isolated system: its nearest neighbor, Ravne 1, is 168 m away (Table 4). These are minimum wall-to-wall distances between surveyed passages. Unsurveyed water-filled or low passages may lie within these gaps (Section 5.2).

4.7. Internal Consistency of the Delivered Data

The drawn axis vertices matched the listed axis-intersection coordinates with median residuals of 1 - 2 mm for every sheet. This confirms that the drawings and coordinate lists are one consistent dataset. It is not a measure of field accuracy (Section 5.3).

The plan footprints re-measured from the georeferenced drawings exceed the reported areas by 0.5% to 2.7%: Ravne 2 by 2.7%, Ravne 3 by 2.6%, Ravne 4 by 1.9%, Ravne 5 by 0.5%, and Ravne 6 by 2.4%. The difference is always positive. That pattern fits the raster method, which counts every cell a boundary line touches. Ravne 1 is drawn as wall lines without a filled footprint, so it could not be checked this way.

5. Discussion

5.1. What a Single Frame Changes

Before 2026 each tunnel had its own plan. Questions about the complex as a whole

could not be answered with measurements. Typical questions were how far apart two systems are, whether they lie at the same level, or what lies under a given patch of ground. The survey now answers them directly. Two results stand out.

First, all six systems share a narrow floor band of 5.57 m. Five of them fall within 3.6 m of each other. This is a measured fact. It is consistent with passages following a preferred horizon in the conglomerate, or a common base level, but the survey cannot tell these apart. Testing that question needs the stratigraphy of the host rock along the passages, not more geometry.

Second, the systems are close but not connected in the surveyed data. Gaps of about 50 m separate Ravne 1 from Ravne 5 and Ravne 4 from Ravne 6. Those gaps are the obvious targets for geophysical prospection or for following unsurveyed passages. The georeferenced model shows exactly where to look.

5.2. Coverage and the Documented Total

The 2452.7 m reported here is surveyed accessible length. It is a lower bound on the network, for two reasons.

The first reason is water. Three water-filled passages could not be scanned in 2026, because the scanners and total station could not be carried through standing water. Their lengths are about 200 m, 154 m and 160 m, or 514 m in total (**Figure 11**). The Foundation's archaeologists estimated them and measured them with a tape under the Foundation's archaeological manager, T. Moon, in 2012-2014. The tape measurements start at the water's edge, where the 2026 scanning stopped, so they are treated as additional to the scanned length. Small overlaps at the transitions

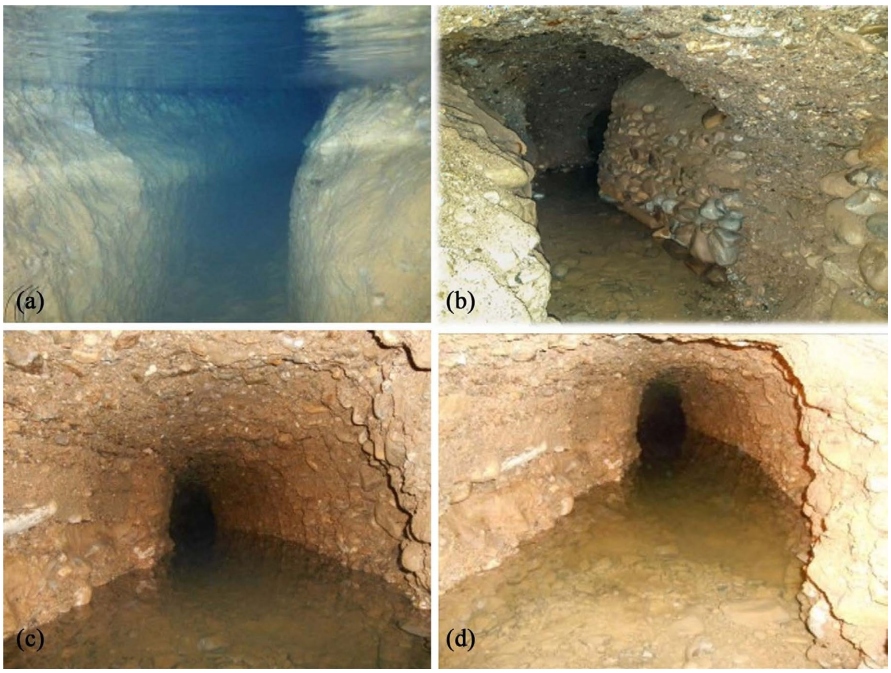

Figure 11. Water-bearing passages of the Ravne network, of the kind that could not be scanned in 2026. (a) Dry-stone wall along a water-bearing passage; (b) Partly submerged corridor; (c) Clear water channel; (d) Water-filled corridor. Adapted from [16], CC BY 4.0.

cannot be excluded. Adding these passages gives a documented subtotal of about 2967 m. Tape lengths are less accurate than scanned lengths, and the subtotal mixes the two methods. It does not verify earlier statements of "over three kilometers" [13], because the low passages described below remain unmeasured.

The second reason is height. Some passages are too low for the scanners and their operators. These include very low sections of Meditation Route 2 and Ravne 4 beyond its first fork. Their lengths were not measured, so they are not added to any total here.

These limits matter for any use of the volume figures. Of the 5490 m^3 total, about 5465 m^3 is the measured open volume of the scanned passages of Ravne 1 and 3 - 6, and about 25 m^3 is the estimate for Ravne 2 (Section 3.5). The total is not the volume of rock removed, and it excludes backfilled sections. Infill and blocking walls are common in the complex [10] [11].

5.3. Accuracy and Reporting Gaps

Achieved accuracies, normal elements of a survey accuracy statement [1] [23] [24], are now reported in **Appendix A**, from the survey records and a supplementary statement by the surveyor [19]. Fitting points and validation points are kept apart. We fitted the UAV LiDAR cloud to eight control points, with a vertical RMS of 0.063 m. At four control points not used in the fit, it agrees with GNSS to 0.069 m horizontally and 0.054 m vertically (RMSE), and at check points T1 - T4 to 0.047 m in height. The tunnel clouds fit the LiDAR surface with cloud-to-cloud errors of 0.031 - 0.035 m. Each tunnel is tied to the common frame only through the LiDAR surface around its entrance, and the overlaps are small (0 - 7%). Absolute positions are therefore good to about 0.1 m, and height differences between systems below about 0.3 m should not be interpreted [22].

Three statistics are unavailable: loop-closure misfits within the TLS registration, each tunnel's internal registration RMS, and LiDAR point density. **Appendix A** marks them explicitly. These gaps matter most for deformation monitoring, where millimeter-level change must be resolved. They are less critical for the lengths, areas, and volumes reported here.

The checks in Section 4.7 complement **Appendix A**. They show that drawings, coordinate lists and reported areas form one consistent dataset, with areas reproducible to within 3%.

The mean widths and heights in **Table 3** are system averages. They hide real variation. Cross-sections cut from the point clouds at regular chainage would give distributions rather than means, and would show where passages narrow. The point clouds already contain this information, but the 2026 deliverables did not include sections.

5.4. Relation to Earlier Published Values

Two earlier figures need updating. The 2025 excavation report gave 496.650 m a.s.l. for Ravne 6 [9]. The 2026 survey places the Ravne 6 floor at 471.33 - 473.50

m. The earlier value should not be read as a floor level. This paper uses the 2026 values throughout. The earlier figure of "over three kilometers" cannot be confirmed: the 2026 survey and the tape measurements document about 2.97 km, and the low passages remain unmeasured (Section 5.2).

5.5. Uses of the Dataset

The dataset now serves as the spatial reference for work in the complex. Researchers can survey new finds, dry-stone walls, and newly opened passages and add them to the GIS database instead of drawing them on separate plans. Repeat scans of the same stations will allow change detection, for example, of wall stability or sediment movement [23]. The microclimate and ion measurements of earlier work can be tied to exact positions and passage dimensions [12]. The same workflow, used at the Kolun hillfort [14], can be repeated at other underground sites in the region.

6. Conclusions

The 2026 survey placed all six Ravne tunnel systems in one georeferenced frame for the first time. It combined a GNSS control network, UAV LiDAR and about 719 TLS stations, and fed the results into CAD and GIS. The main results are:

1) The surveyed accessible network is 2452.7 m long, with 3379.6 m^2 of floor area and about 5490 m^3 of open volume, including an estimated 25 m^3 for Ravne 2. Ravne 1 holds 70% of the length.

2) Passages average 1.38 m wide and 1.62 m high.

3) All floors lie within a 5.57 m band (469.93 - 475.50 m a.s.l., BH_VRS1971.5). Mean gradients are 0.94% - 2.0%.

4) Ravne 2, 4 and 5 are elongated corridors. Ravne 1, 3 and 6 are compact branching networks.

5) No two systems connect in the surveyed data. The closest pairs are about 50 m apart.

6) About 514 m of tape-measured water-filled passages, and an unmeasured length of low passages, remain unscanned. With the water-filled passages, the documented subtotal is about 2.97 km.

Three tasks remain. Loop-closure statistics should be extracted from the registration projects. Cross-sections should be cut at regular chainage. Other methods, such as handheld or mobile scanning, should survey the water-filled and low passages. The dataset already gives later archaeological, geological and environmental work a common spatial basis.

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Author Contributions

Sam Osmanagich: conceptualization, analysis of the delivered survey data, independent checks (Section 3.7), writing of the original draft, review and editing. Alija Žutić: design and supervision of the survey; GNSS, UAV LiDAR and TLS data acquisition and processing; description of the survey methods and accuracy assessment (**Appendix A**); review and editing. Both authors have read and approved the final manuscript.

Data Availability

The survey report, drawings, coordinate lists and point clouds (E57) are held by the Archaeological Park: Bosnian Pyramid of the Sun Foundation. They are available from the authors on reasonable request, as are the floor and ceiling point lists and the supplementary accuracy statement [19].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix A. Reference Frame and Achieved Accuracy

All values are from the survey records and the surveyor's supplementary statement [19]. Points used to fit a product are marked as fitting points; points not used in the fit are marked as validation points. Statistics that the records do not contain are marked as not available.

Table A1. Reference frame and transformation.

Element	Value
Horizontal system	MGI/Balkans zone 6 (EPSG:31276); Bessel 1841 ellipsoid; Gauss-Krüger projection, central meridian 18˚E
Transformation	Seven-parameter similarity, WGS84/GRS80 to Bessel 1841, adopted from the Visoko municipal survey office: ΔX = −403.6292 m, ΔY = −194.6950 m, ΔZ = −596.2218 m; RX = 5.68536″, RY = 8.06339″, RZ = −13.32216″; scale = −3.2289 ppm
Vertical system	BH_VRS1971.5 (second high-accuracy levelling; mean sea level at five Adriatic tide gauges, epoch 1971.5)
Geoid/quasigeoid model	Not available (not recorded in the survey documentation)
RTK corrections	FBiHPOS permanent GNSS station network (RTCM), for control points and UAV flight

Table A2. Achieved accuracy by processing stage.

Stage	Points	Role	Statistic	Value (m)
GNSS control	GG1 - GG15	Solution quality	Software RMS (HRMS/VRMS)	0.025 - 0.040 (0.01 - 0.02/0.02 - 0.03)
GNSS check points	T1 - T4	Solution quality	RMS, HRMS, VRMS	0.01 each
UAV LiDAR to control	GG1, GG2, GG3, GG5, GG7, GG9, GG11, GG12	Fitting	3D residual mean/RMS/max	0.114/0.119/0.163
		Fitting	RMS horizontal/vertical	0.101/0.063
UAV LiDAR vs GNSS	GG6, GG8, GG14, GG15	Validation	RMSE horizontal/vertical/3D	0.069/0.054/0.088
	T1 - T4	Validation (height only)	RMSE vertical; max |ΔH|	0.047; 0.059
	All 12 identifiable GG points	Mixed (8 fitting + 4 validation)	RMSE horizontal/vertical/3D	0.086/0.062/0.106
			Mean shift X (significant at α = 0.05)	+0.037
TLS to UAV LiDAR	Six tunnel clouds	Fitting	Cloud-to-cloud error, overall (per tunnel)	0.033 (0.031 - 0.035)
TLS internal registration	Per tunnel	—	Registration RMS	Not available
TLS loop closures	Ravne 1 and other closed loops	—	Closure misfit	Not available
UAV LiDAR flight	—	—	Point density; flight speed	Not available

GG4, GG10 and GG13 could not be identified in the LiDAR cloud and are excluded from the comparisons. The eight fitting points correspond to the RealWorks targets 001 - 008. The horizontal mean shift of +0.037 m in X is common to all twelve points and was not corrected.

Table A3. Fit of the tunnel clouds to the UAV LiDAR surface (Trimble RealWorks).

Tunnel	Cloud-to-cloud error (mm)	Common points (%)	Confidence (%)
Ravne 1	35.20	3	0
Ravne 2	32.05	4	100
Ravne 3	33.17	0	0
Ravne 4	34.02	4	100
Ravne 5	34.03	3	0
Ravne 6	30.59	7	100
Overall	33.18	—	—

The low overlap and confidence values reflect the small entrance zones relative to the area of the LiDAR cloud [19].