Contributions to Geophysics and Geodesy Vol. 54/4, 2024 (389–406)

Preliminary estimate of current ice thickness in the Dobšiná Ice Cave by means of geophysical and geodetic methods

Roman PAŠTEKA[1,*], Pavol ZAHOREC[2], Ivan ŠULEK[1], Erik ANDRÁSSY[3], Juraj PAPČO[4], Katarína PUKANSKÁ[5], Ema NOGOVÁ[2], Dominika GODOVÁ[6], Lenka ONDRÁŠOVÁ[2], Jozef BÓDI[2]

[1] Department of Engineering Geology, Hydrogeology and Applied Geophysics, Faculty of Sciences, Comenius University, Ilkovičova 6, 842 15 Bratislava, Slovak Republic

[2] Earth Science Institute, Slovak Academy of Sciences, Bratislava/Banská Bystrica, Slovak Republic

[3] Water-Management Construction – State Enterprise, Department of Geology and Environmental Impacts, Bratislava, Slovak Republic

[4] Department of Theoretical Geodesy and Geoinformatics, Faculty of Civil Engineering, Slovak University of Technology, Bratislava, Slovak Republic

[5] Institute of Geodesy, Cartography and Geographical Information Systems, Faculty of Mining, Ecology, Process Control and Geotechnologies, Technical University of Košice, Slovak Republic

[6] Institute of Geophysics Czech Academy of Sciences, Prague, Czech Republic

Abstract: The presented study focuses on the Dobšiná Ice Cave, which is worldwide unique from the speleological viewpoint, belonging to the most famous caves in Europe. During the 20th century, the research of the cave was carried out within various scientific branches. In the last years, one important part of the survey is the geodetic monitoring of the ice surface by modern laser scanning methods. Since 2020, also geophysical (georadar and microgravity) research is conducted in the Dobšiná Ice Cave. In this contribution, we present preliminary results on the present ice filling thickness, based on the interpretation of vertical radargrams and 2.5D density modelling of anomalous gravity data. Maximum thickness values from georadar measurements are more than 24.5 m in the eastern part of the cave, in the lower part of the Great Hall. Roughly estimated error of the depth determination from GPR vertical sections is at the level of ±0.5 m. Results from gravimetry apparently point to the fact that the sections with largest ice thickness could be placed rather westward to the central part of the cave. This interpretation remains questionable though, still open due to missing GPR results in the central part of the cave. We hope that future additional data and 3D density modelling will help to resolve this issue.

---

[*] corresponding author, e-mail: roman.pasteka@uniba.sk

doi: 10.31577/congeo.2024.54.4.5

Key words: ground penetrating radar, microgravity method, migration, topographic effect

1. Introduction

Possibilities of applied geophysical surveys are very diverse and have an impact on various geoscience, environmental and engineering disciplines (e.g. *Milsom and Eriksen, 2011; Reynolds, 2011*). Among them, a very interesting chapter is the geophysical survey of the internal structure of caves, as well as the discovery of new spaces in karst areas (e.g. *Beres et al., 2001; Pepe et al., 2013; Putiška et al., 2014*). Very interesting type of karstic structures are ice caves. These are not only beautiful natural formations, but also a huge archive of geological and biological data preserved in their ice fillings. Research of ice caves is very important – mainly from the point of view of the study of the thickness of their glaciation and the overall internal structure, to which a number of studies and publications have been devoted (e.g. *Hausmann and Behm, 2011*). An important part is, of course, the geodetic survey of these underground spaces, which provides independent scientific output (e.g. *Bartoš et al., 2023*; *Dušeková et al., 2024*), as well as support for geophysical research – which would not be possible to implement without precise positional-spatial focus in demanding conditions of underground spaces.

Our presented study is focused on the Dobšiná Ice Cave, which is unique in the world from the point of view of speleology and is among the most famous caves in Europe (belongs also into the group of UNESCO Natural Heritage sites). It is located near the town of Dobšiná in eastern Slovakia. The monumental glaciation of the Dobšiná Ice Cave lasts for a millennium at an altitude of only 920 to 950 m above sea level – when compared to similar caves in Austria and Romania, whose glaciated parts are located at heights above 1000 m above sea level. The cave was discovered in 1870 and its scientific research began practically from the date of its discovery. For example, already in 1870–1871, the first meteorological measurements were carried out – at that time these measurements were mainly focused on the determination of seasonal temperature fluctuations in the cave (e.g. *Jerg, 2020*). During the 20th century, the research of the cave was carried out within various scientific branches – such as speleological, geological, hydrological, climatological, geomorphological, geodetic, paleoclimatological and biospeleological research (e.g. *Jákal, 1971; Novotný and Tulis, 1996; Bella, 2003*). Thanks to a significant technological shift in the field of modern geodesy, very precise measurements of the ice surface could be carried out in the cave in recent years – using laser scanning and tachymetry (*Bartoš et al., 2023; Dušeková et al., 2024*). From 2020, a geophysical survey was also started in the Dobšiná Ice Cave with the aim of estimating the thickness of the ice using various geophysical methods (*Pukanská et al., 2024*). In the presented article, we present the preliminary results of the mentioned research. It should be noted that a georadar survey (with a 100 MHz antenna) was carried out in the cave already at the end of the 20th century (*Géczy and Kucharič, 1995*), the results of which are very valuable material for comparing the changes in ice thickness that have occurred over the past decades. The first estimates of the volume of ice in the cave date back to 1871, when the value was estimated at 125,000 m^3 (*Pelech, 1884*), later estimates (*Droppa, 1960*) gave a value of 145,000 m^3. We hope that the results of our study will over time contribute to the refinement of the ice model in the Dobšiná Ice Cave – more precisely, they will contribute to the refinement of the topography of the ice bed. In the next part of the paper, we will discuss in more detail the geophysical methods used and the results obtained.

2. Methods

Geophysical methods are based on the acquisition, processing and interpretation of various geophysical fields. In the near-surface geophysics, the mostly used methods are electro-magnetic methods, DC-geoelectrical methods, seismic methods and potential fields methods – magnetometry and gravimetry (e.g. *Reynolds, 2011*). Among all these listed methods, we have tested and conducted following methods: GPR (ground penetrating radar), microgravimetry (very detailed gravimetry) and seismic method (refractions seismics). Important was to select such a method, where the contact between the ice-filling and the base-rock is well displayed in the contrast of petro-physical properties of both environments. In the case of the GPR and microgravity method this condition is quite well fulfilled (complications can be caused by the volumes of underlying debris between the ice and bedrock), but unfortunately the seismic refraction method was not able to recognise this kind of boundary. Use of the GPR method in the exploration of ice caves is of course not new – it was successfully applied in many previous studies and projects (e.g. *Hausmann and Behm, 2011; Colucci et al., 2016; Gómez Lende et al., 2016; Securo et al., 2022*). The implementation of the microgravity method is relatively new – at least for authors of this contribution, there are unknown other cases of the application of this method in ice caves.

The GPR method (often referred as georadar) is a geophysical method, which is based on the electro-magnetic (EM) emission and its penetration into the soil and rock environment. EM emissions are created by a transmitting antenna, which is a build-in part of the GPR-instrument. It usually operates with higher frequencies – these have typically values of several hundreds of MHz (used values are from 50 to 2000 MHz). Emitted pulses of EM emissions are reflected from subsurface structures and boundaries – and after their return back to the instrument, these are registered by so called receiver antenna. Registered signals are later processed by means of special approaches, due to the wave character of the acquired data. In preliminary stage of processing 2D vertical time-sections (radargrams) are usually the

Fig. 1. Geophysical data acquisition in the Dobšiná Ice Cave (left: georadar measurements, right: gravimetrical measurements).

first data for further processing and interpretation (e.g. *Milsom and Eriksen, 2011*). More advanced and challenging is the 3D processing – but this approach could not be used during the conducted survey in the Dobšiná Ice Cave, due to the difficult field conditions. In the case of Dobšiná Ice Cave exploration, we have used the MALA Ground Explorer (GX) instrument with the 160 MHz antenna (Fig. 1, left). Data acquisition itself was conducted along selected lines with different lengths – in total of 16 lines (Fig. 2) (sequence numbers of new GPR lines vary from nr. 1 to nr. 20, with some numbers being skipped). Absolute majority of the GPR lines was situated in the Great Hall (Fig. 2), where the surface of the ice is well accessible. Some of the lines were positioned in a close vicinity with the previously acquired GPR lines in year 1995 (Fig. 2, black line-segments).

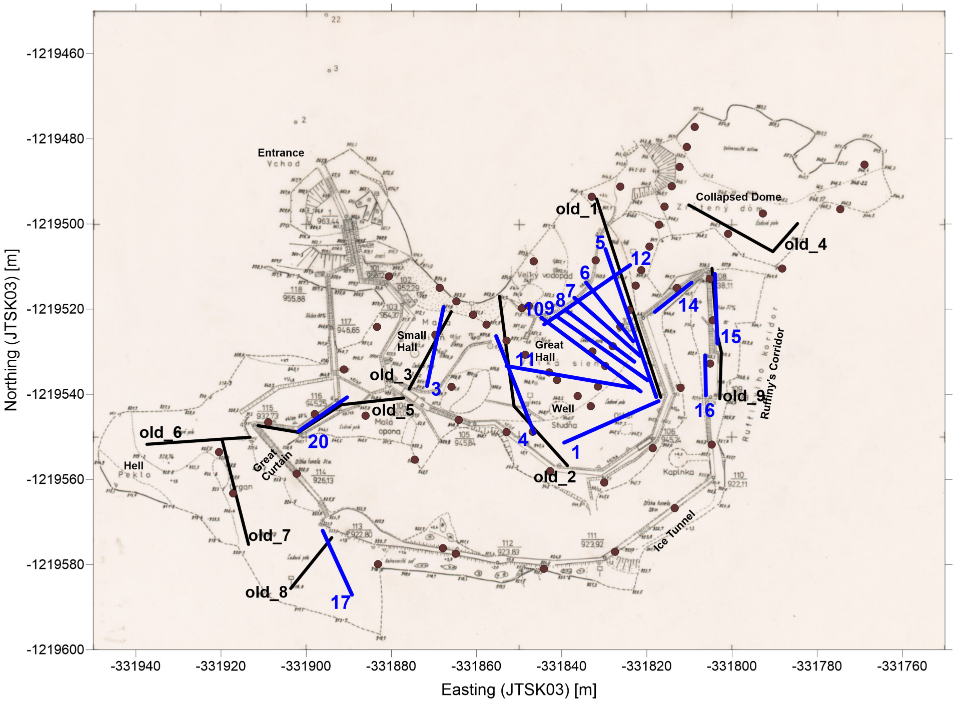

Fig. 2. Positions of geophysical measurements in the Dobšiná Ice Cave (black line-segments: old GPR lines from 1995, blue line-segments: new GPR lines from 2020–2024, brown dots: gravimetric points). Areal plan of the the Dobšiná Ice Cave was modified from the original of *Sýkora et al. (1982)* in *Géczy and Kucharič (1995).*

Example of a comparison of GPR radargrams from measurements in 1995 and 2020 is given in Fig. 3 (line nr. 3) – we will come back to this comparison later in the paper.

Gravimetry (or microgravimetry) is a method suitable for detecting shallow subsurface objects with significant density contrast such as crypts in archaeology (e.g. *Pašteka et al., 2020*), mines (e.g. *Bishop et al., 1997*) or caves (e.g. *Butler, 1984*). The ice filling of caves, due to its low density, can also be a suitable example for the use of gravimetry. The aim of this article is to show an approximative 2D model of the ice fill of the Dobšiná Ice Cave and compare it with GPR results. Dobšiná Ice Cave is a special case for gravimetry, for several reasons. The gravity measurement itself is a bit more complicated than on the Earth's surface. Measuring on ice is unstable, as the ice is easily deformed due to the weight of the gravimeter. Therefore, a special steel pad under the gravimeter tripod was used for the measurement. Two Scintrex CG-5 gravity meters (Fig. 1, right) were

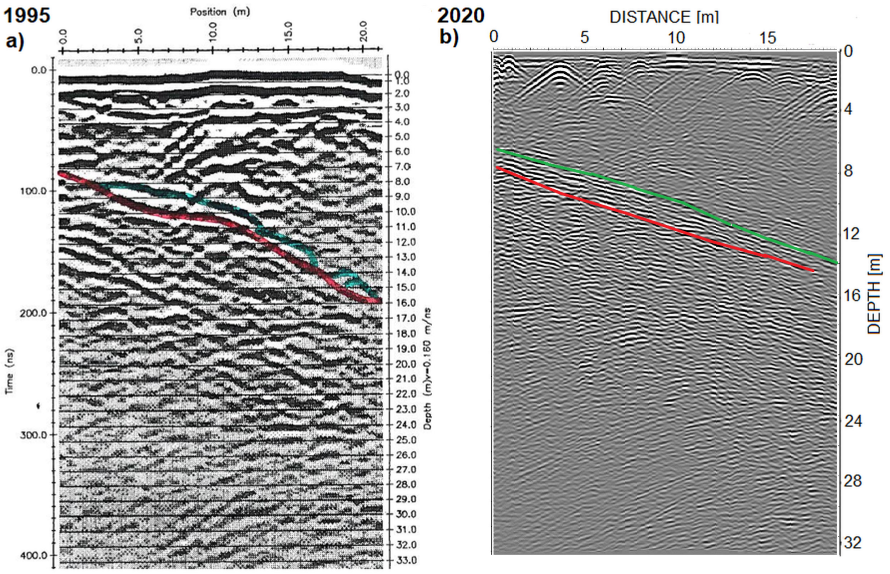

Fig. 3. Comparison of vertical radargrams from a selected GPR line (line nr. 3): a) acquired in year 1995 (*Géczy and Kucharič, 1995*); b) acquired in year 2020 (this study). Green curved line is showing the bottom boundary of the ice layer, the red curved line is showing the bottom boundary between the underlying debris and the bedrock.

used for the measurements. A stable base point (on rocky ground outside the ice) was located inside the cave, on which measurements were taken to check the drift of the gravity meters. The reference point was located outside the cave in order to eliminate any seasonal gravity changes inside the cave. Despite the above mentioned complications, the estimated gravity error from the repeated measurements (by two gravimeters) was approximately $\pm 8\,\mu$Gal (8.10^{-8} m/s^2), what is sufficient accuracy. Finally, values of complete Bouguer anomaly were calculated for the correction density of 2670 kg/m^3.

Positions and heights of all points and profile lines were precisely measured by means of laser tachymetry, utilising monumented geodetic points on stable cave walls (prepared by experts from the Institute of Geodesy, Cartography and Geographical Information Systems, Technical University of Košice).

3. Results

Acquired GPR data along 16 measured lines (Fig. 2) were processed in software ReflexW (*Sandmeier, 2020*), using standard 2D steps: start-time removal, background removal, mean subtraction (dewow), application of a gain function, correction for topography and migration (example of selected line nr. 20 is shown in Fig. 4). Due to the variable topography of the ice in some parts of the cave, the introduction of topographic corrections was very important. Precise topography was interpolated from in-situ geodetic measurements during GPR data acquisition, utilising laser tachymetry. All radargrams are dominated by manifestation of the ice layer in the upper part – this part of the section has much less reflections and is more homogeneous (e.g. Fig. 4d). On the other hand, there are still isolated diffraction waves in the ice layer – caused by isolated blocks of stones that fell from the ceiling of the cave. These diffraction waves are disturbing during the detection of the base of the ice, but at the same time these are very helpful for the estimation of the velocity of EM waves in the ice – by means of the velocity hyperbolas approximation. Estimated value 0.16 m/ns (Fig. 5) fits perfectly with the results of the CMPS method (Common-Mid-Point Sounding), which was applied during the study by *Géczy and Kucharič (1995)*. The stated velocity of 0.16 m/ns was later used in our actual study during

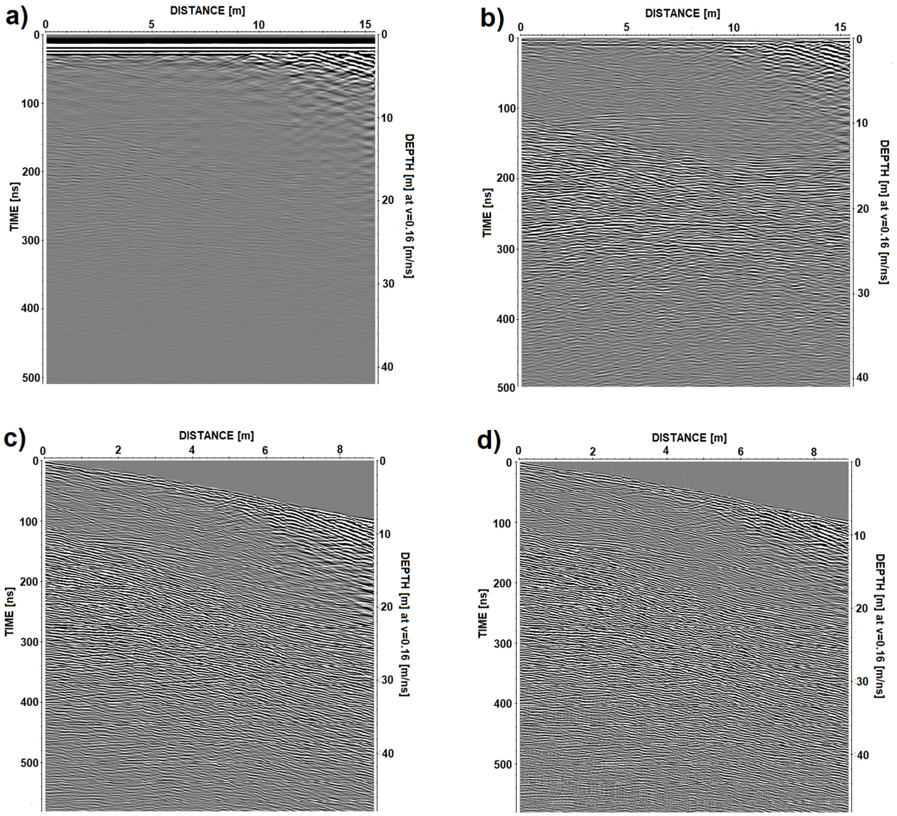

Fig. 4. Sequence of partial outputs from the GPR data 2D processing in a form of vertical radargrams (line nr. 20): a) acquired data with application of a gain function; b) application of start-time and background removal, together with mean subtraction (dewow); c) application of the correction for topography; d) application of the migration processing step.

all conversions of the TWT (Two-Way-Time) values to actual depths.

Very important processing step was the migration procedure. It helped to remove (partly) the disturbing diffraction waves and has made the recognition of the bottom boundary of the ice clearer (nice example is shown in Fig. 6 at line nr. 12). Not all lines have given such nice results (as in the case of line nr. 12). In some of them, there appears a problem with the underlying debris between the ice layer and bedrock. This bottom boundary (debris – bedrock) can be distinguished in some cases only hardly, because

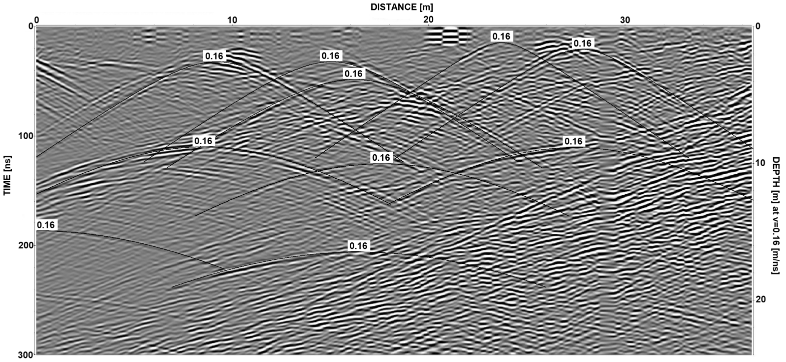

Fig. 5. Selected part from a vertical radargram (line nr. 5) with picked diffraction hyperbolas – used for the velocity estimations. Values 0.16 in small white rectangles (positioned on the tops of hyperbolas) represent estimated velocity value 0.16 m/ns. Presented procedure was conducted on sections before applying the correction for topography.

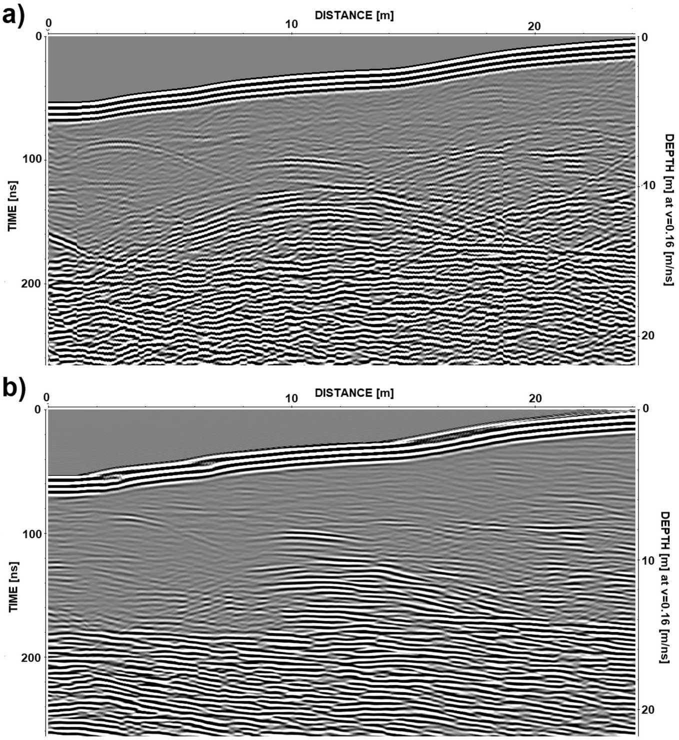

Fig. 6. Vertical radargrams (line nr. 12) without migration (a) and with migration (b).

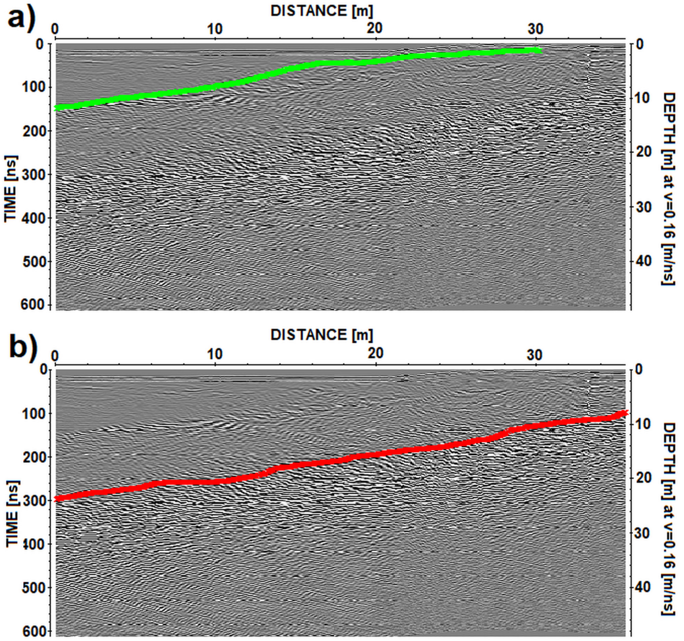

Fig. 7. Interpretation of the bottom boundary of the ice layer (a) and the boundary between the debris and the bedrock (b), demonstrated on the GPR line nr. 5.

of a very common reflection pattern of the debris and bedrock in the radargrams (Fig. 7). For the estimation of the ice filling of the cave, we took the depths to the boundary of the bedrock (from measurements conducted in 2022–2024). Based on these estimates, we created a preliminary map of ice thickness in the cave (Fig. 8). Maximum thickness values are more than 24.5 m in the eastern part of the cave, in the lower part of the Great Hall (Fig. 8). The roughly estimated error of the depth determination from GPR vertical sections is at the level of ±0.5 m. In the map of Fig. 8, it can be seen that not the whole area of the cave could be covered by GPR measurements. Consequently, in the south-western part of the cave, the obtained results are strongly impacted by interpolation errors.

An important task was to compare the current results of GPR measurements with those from 1995. After several independent trials, it turned out that the said comparison is not at all easy to perform. We have managed to place some of our new lines in the locations of the profiles from 1995 (Fig. 2,

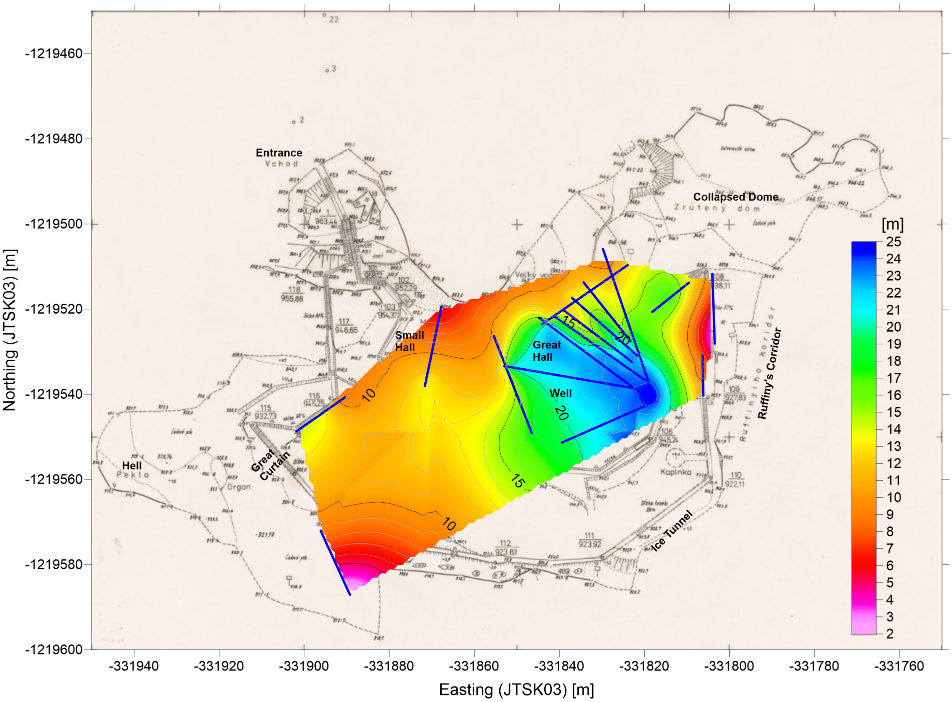

Fig. 8. Map of the ice filling thickness (ice layer together with debris), based on the interpretation of GPR data.

profiles 3, 4 and 5 in the Great Hall). But to perform the exact comparison of the thicknesses of the ice filling, we lack the precise height measurements of the ice surface from 1995. Approximate comparisons showed that the estimated differences between the determined ice thicknesses in 1995 and those from 2022–2024 are at the level of ±0.5 m, which is actually at the level of the estimated error of the determination of the mentioned parameter from GPR. We plan to continue pursuing this task in the future. At the moment we are not able comment on it in a more reliable way.

Results from gravimetry brought also very interesting information. We have to emphasize that the cave is very specific in terms of data processing. Since measurements were performed underground, it is necessary to emphasize the correct calculation of the topographic effect (or terrain correction), including the gravitational effect of the cave itself. State-of-the-art procedures were used: proven Toposk software designed for any position of the calculation point, i.e. even below the Earth's surface (*Zahorec et al., 2017*), detailed digital elevation model *DEM5.0* based on aerial laser scanning (`https://www.geoportal.sk/sk/zbgis/lls-dmr/`) and a spatial model of the cave derived from terrestrial laser scanning (TLS) and tachymetry (*Pukanská et al., 2024*). In addition, the overall configuration of the space and measurement stations is specific. Figure 9 shows a schematic situation across the cave. Measurements were taken at two levels of the cave: the upper level (Great Hall), where the measurement points are situated above the ice fill level, and the lower level (Corridor in Fig. 9), where the measurement points are located below the ice fill level. The volume of ice between these cave levels is difficult to estimate, as it is inaccessible to direct observation (Fig. 9). Such a specific situation of the distribution of measurement points relative to the anomalous source is also reflected in the shape of the complete Bouguer anomaly (CBA) map: along the lower corridor it reaches relatively positive anomalous CBA values, while at the upper level (above the ice level) it reaches negative values, as expected (Fig. 10).

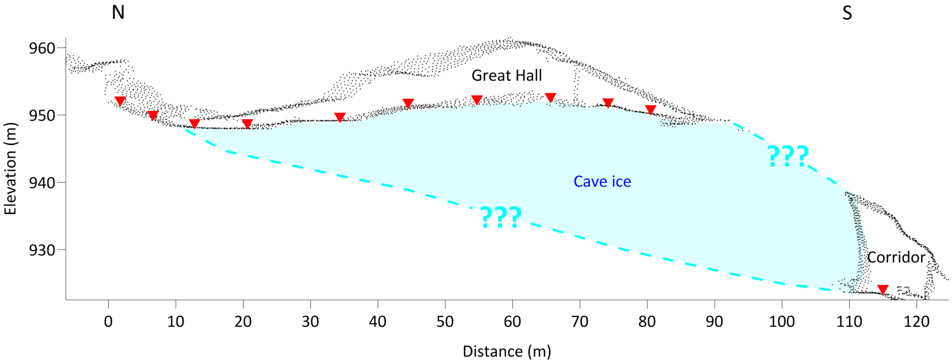

Fig. 9. Schematic spatial situation across the cave. Cave spaces are taken from TLS (point clouds). The red symbols schematically show the location of gravimetric measurement points on the upper (Great Hall) and lower (Corridor) levels of the cave.

For the 2D interpretation of ice thickness, we chose a profile passing approximately through the centre of the anomalous area (Fig. 10), connecting the measured gravity points in both the Great Hall and the lower corridor (Figs. 9 and 10). The density model was obtained using the GM-SYS software in a 2.5D modelling approach. A differential density of -1750 kg/m^3 was used for the ice, as the difference between the actual density of ap-

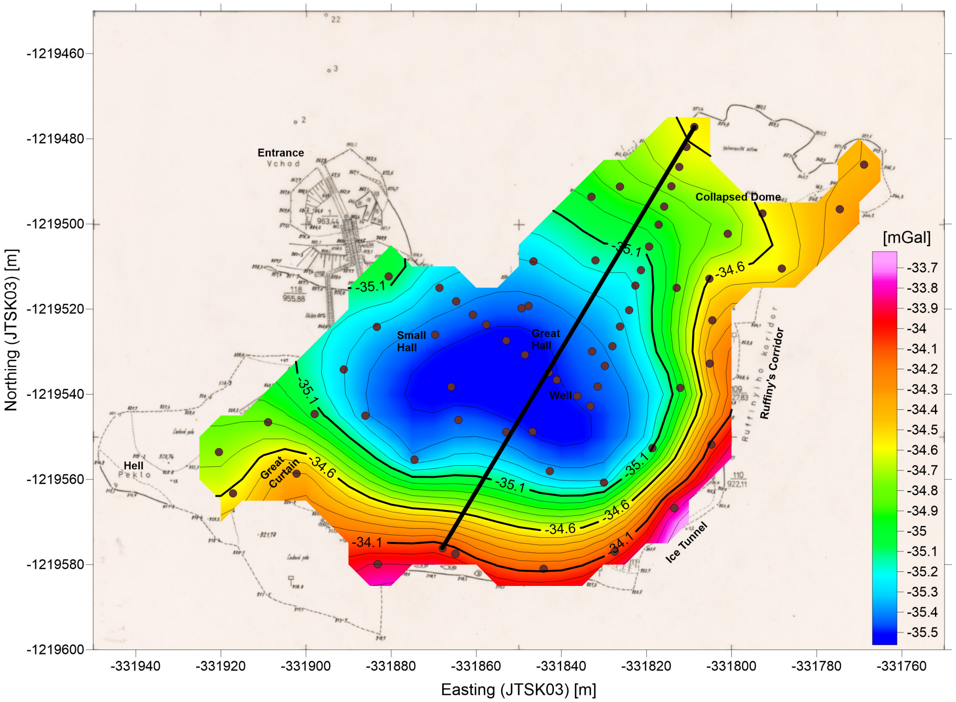

Fig. 10. Complete Bouguer Anomaly (CBA) map for the correction density 2670 kg/m^3. Brown dots represent gravimetric points. The long black line-segment indicates the selected interpreted profile using 2.5D density modelling.

prox. 920 kg/m^3 and the CBA correction density of 2670 kg/m^3. The density model is shown in Fig. 11. The interpreted ice thickness reaches about 20 m and correlates quite well with the GPR results. It seems that a good fit between the result of density modelling and GPR interpretation is in the case of the ice-layer thickness itself – because for gravimetry there is a larger density contrast. In the lower part of the profile (the inaccessible area between the two levels of the cave), the interpretation is only schematic. More information could be provided in the future by 3D modelling of the cave's ice filling. When we plot together the ice filling thickness (ice layer together with debris) from GPR (Fig. 8) and the contours CBA (Fig. 10) into one figure (Fig. 12), then we can see that the position of the CBA minimum is shifted westwards, compared with the maximum of ice filling from GPR data. Results from gravimetry are apparently pointing to the fact that the

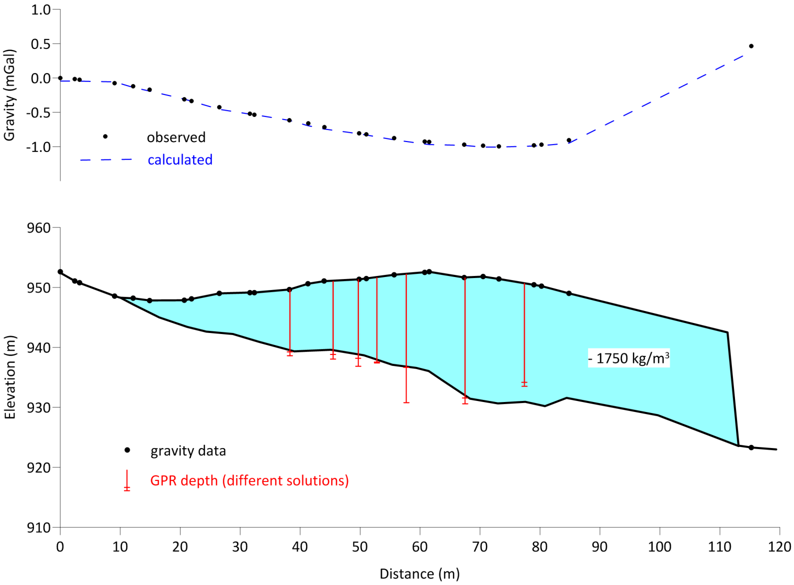

Fig. 11. Ice fill model based on 2.5D density modelling with GM-SYS software. Black dots indicate gravity data (interpolated from the CBA map). Part of the profile is not covered by measurements (see the situation in Figs. 9 and 10). Red line-segments in the bottom part of the figure show interpreted GPR depths (shallower depth represents the bottom of the ice layer, the deeper depth represents the bottom of the underlying debris).

parts with large ice thickness could be shifted more to the central part of the cave (in the western direction). However, we must keep in mind that the relief of the ice surface changes significantly in this part of the cave, which may cause a shift in its maximum effect. This interpretation is questionable and still open, because there are missing GPR results in the central part of the cave. We hope that future 3D density modelling will help to resolve this issue.

4. Conclusions

Research in ice caves is very important from both speleological and climate perspectives. Joint geodetic and geophysical investigation can provide valuable insights useful for other scientific disciplines. The presented study focuses on the Dobšiná Ice Cave, a worldwide unique cave from the point of view of speleology. It is also among the most famous caves in Europe.

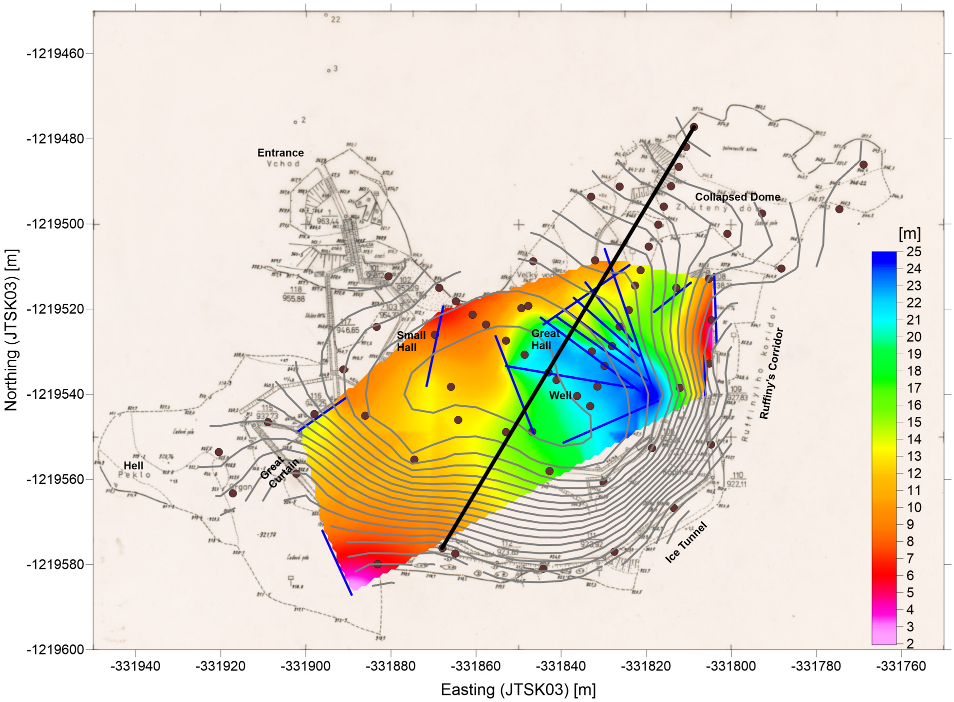

Fig. 12. Map of the ice filling thickness (ice layer together with debris) – displayed as a coloured image map, together with contours of the CBA map for the correction density 2670 kg/m^3. Brown dots represent gravimetric points, blue line-segments represent new GPR lines from 2020–2024. The long black line-segment indicates the selected interpreted profile using 2.5D density modelling.

Since 2020, georadar (GPR) and microgravimetric research is performed in the cave. Both methods had to deal with methodological and logistic challenges, due to observing in a cave. In the GPR interpretation, the problem was to recognize the boundary between debris and bedrock. In gravimetry, the challenge was mainly to calculate the topographic correction, accounting both for the earth surface and the cave ceiling, as well as the void cave space.

We present here preliminary results on the thickness of the actual ice filling in the cave (ice layer and underlying debris). The maximum thickness values attain more than 24.5 m in the eastern part of the cave, specifically in the lower part of the Great Hall. The grossly estimated error of the depth estimation from GPR vertical sections is at the level of ±0.5 m. Interpretation of the acquired anomalous gravity data was performed by means of 2.5D density modelling approach with a differential density contrast of -1750 kg/m^3 of ice, along a central line crossing the cave. The interpreted ice thickness reaches about 20 m and correlates quite well with the GPR results. On the other hand, results from gravimetry apparently point to the fact that those parts with large ice thickness could be located more to the central part of the cave (more westwards). This interpretation is questionable and still open, because there are missing GPR results in the central part of the cave. We hope that future additional data and 3D density modelling will help to solve this problem. At the moment, there are still places in the cave, where we do not have new geophysical data, such as the south-west part, nicknamed "Hell".

Acknowledgements. Presented study was supported by the project of the Scientific and Grant Agency of the Slovak Republic VEGA 1/0340/22 "Research of spatial structure and changes of surface and subsurface geosystems by geodetic and geophysical methods" and partly by projects APVV-19-0150 and APVV-21-0159. Field data acquisition was supported by the Slovak Caves Administration Agency.

References

Bartoš K., Pukanská K., Kseňak Ľ., Gašinec J., Bella P., 2023: Cross-Polarized SfM Photogrammetry for the Spatial Reconstruction of Challenging Surfaces, the Case Study of Dobšiná Ice Cave (Slovakia). Remote Sens., **15**, 18, 4481, `doi: 10.3390/rs15184481`.

Bella P., 2003: Glacial ablation forms in Dobšiná Ice Cave. Aragonit, **8**, 3–7 (in Slovak with English summary).

Beres M., Luetscher M., Olivier R., 2001: Integration of ground-penetrating radar and microgravinetric methods to map shallow caves. J. Appl. Geophys., **46**, 4, 249–262, `doi: 10.1016/S0926-9851(01)00042-8`.

Bishop I., Styles P., Emsley S. J., Ferguson N. S., 1997: The detection of cavities using the microgravity technique: case histories from mining and kartic environments. In: McCann D. M., Eddleston M., Fenning P. J., Reeves G. M. (Eds.): Modern Geophysics in Engineering Geology. Geological Society Engineering Geology Special Publication, **12**, 153–166, `doi: 10.1144/GSL.ENG.1997.012.01.13`.

Butler D. K., 1984: Microgravimetric and gravity gradient techniques for detection of subsurface cavities. Geophysics, **49**, 7, 1084–1096, `doi: 10.1190/1.1441723`.

Colucci R. R., Fontana D., Forte E., Potleca M., Guglielmin M., 2016: Response of ice caves to weather extremes in the southeastern Alps, Europe. Geomorphology, **261**, 1–11, `doi: 10.1016/j.geomorph.2016.02.017`.

DEM5.0: Aerial Laser Scanning – DEM (Letecké laserové skenovanie – DMR). Geodetic and Cartographic Institute Bratislava, retrieved November 15, 2024, accessible at: `https://www.geoportal.sk/sk/zbgis/lls-dmr/`.

Droppa A., 1960: Dobšiná Ice Cave. Šport, Bratislava, Slovakia, 115 p. (in Slovak with Russian, German and French summary).

Dušeková L., Herich P., Pukanská K., Bartoš K., Kseňak Ľ., Šveda J., Fehér J., 2024: Comparison of Non-Contact Measurement Technologies Applied on the Underground Glacier—The Choice for Long-Term Monitoring of Ice Changes in Dobšiná Ice Cave. Remote Sens., **16**, 20, 3870, `doi: 10.3390/rs16203870`.

Géczy J., Kucharič Ľ., 1995: Determination of morphometric parameters from glaciated parts of the Dobšiná Ice Cave. Report – manuscript. ECS Environmental Consulting Services Slovakia Ltd., 26 p. (in Slovak).

Gómez Lende M., Serrano E., Bordehore L. J., Sandoval S., 2016: The role of GPR techniques in determining ice cave properties: Peña Castil ice cave, Picos de Europa. Earth Surf. Process. Landf., **41**, 15, 2177–2190, `doi: 10.1002/esp.3976`.

Hausmann H., Behm M., 2011: Imaging the structure of cave ice by ground-penetrating radar. Cryosphere, **5**, 329–340, `doi: 10.5194/tc-5-329-2011`.

Jákal J., 1971: Morphology and genesis of the Dobšiná Ice Cave. Slovak Karst Journal, **9**, 27–41 (in Slovak).

Jerg Z., 2020: Nándor Fehér – co-discoverer of the Dobšiná Ice Cave and initiator of its scientific research. Slovak Karst Journal, **58**, 1, 117–141, ISSN 0560-3137 (in Slovak).

Milsom J., Eriksen A., 2011: Field Geophysics, 4th ed. John Wiley and Sons, 232 p., ISBN: 9780470749845.

Novotný L., Tulis J., 1996: The results of the latest research in the Dobšiná ice cave. Slovak Karst Journal, **34**, 139–147 (in Slovak).

Pašteka R., Pánisová J., Zahorec P., Papčo J., Mrlina J., Fraštia M., Vargemezis G., Kušnirák D., Zvara I., 2020: Microgravity method in archaeological prospection: methodical comments on selected case studies from crypt and tomb detection. Archaeol. Prospect., **27**, 4, 415–431, `doi: 10.1002/arp.1787`.

Pelech J. E., 1884: Das Stracenaer Thal und die Dobschauer Eishöhle (The Stracena Valley and the Dobschau Ice Cave). Buchdruckerei des Franklin-Verein, Budapest, Hungary, 51 p. (in German).

Pepe P., Pentimone N., Garziano G., Martimucci V., Parise M., 2013: Lessons learned from occurrence of sinkholes related to man-made cavities in a town of southern Italy. In: Land L., Doctor D. H., Stephenson J. B., (Eds.): Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Carlsbad (New Mexico, USA), 6–10 May 2013, Carsbad, National Cave and Karst Research Institute, 393–401, `doi: 10.5038/9780979542275.1150`.

Pukanská K., Bartoš K., Gašinec J., Pašteka R., Zahorec P., Papčo J., Bella P., Andrássy E., Dušeková L., Bobíková D., Kseňak Ľ., 2024: Methodological Approaches to Survey Complex Ice Cave Environments – The Case of Dobšiná (Slovakia). Front. Environ. Sci., **12**, 1484169, `doi: 10.3389/fenvs.2024.1484169` (accepted, in press).

Putiška R., Kušnirák D., Dostál I., Lačný A., Mojzeš A., Hók J., Pašteka R., Krajňák M., Bošanský M., 2014: Integrated geophysical and geological investigations of karst structures in Komberek, Slovakia. J. Cave Karst Stud., **76**, 3, 155–163, `doi: 10.4311/2013ES0112`.

Reynolds J. M., 2011: An Introduction to Applied and Environmental Geophysics, 2nd ed. John Wiley and Sons, 710 p., ISBN: 978-0-471-48535-3.

Sandmeier K. J., 2020: REFLEXW Version 9.5 manual. Manuscript, 709 p., accessible at: `https://www.sandmeier-geo.de/`.

Securo A., Forte E., Martinucci D., Pillon S., Colucci R. R., 2022: Long-term mass-balance monitoring and evolution of ice in caves through structure from motion–multi-view stereo and ground-penetrating radar techniques. Prog. Phys. Geogr. Earth Environ., **46**, 3, 1–19, `doi: 10.1177/03091333211065123`.

Sýkora J., Lalkovič M., Thuróczy J., Kadlečík Ľ., 1982: Map of Dobšiná ice cave based on in-situ geodetic measurements. Manuscript, Slovak Caves Administration Agency, 1 p. (in Slovak).

Zahorec P., Marušiak I., Mikuška J., Pašteka R., Papčo J., 2017: Numerical Calculation of Terrain Correction Within the Bouguer Anomaly Evaluation (Program Toposk) – Chapter 5. In: Pašteka R., Mikuška J., Meurers B.: Understanding the Bouguer Anomaly: A Gravimetry Puzzle. Elsevier, Amsterdam, 79–92, ISBN 978-0-12-812 913-5, `doi: 10.1016/B978-0-12-812913-5.00004-X`.