Applied Acoustics 197 (2022) 108929

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Technical note

Acoustics of icelandic lava caves

Paweł Małecki [a,*], Tomasz Lipecki [b], Dorota Czopek [a], Janusz Piechowicz [a], Jerzy Wiciak [a]

[a] Department of Mechanics and Vibroacoustics, AGH University of Science and Technology, al. A. Mickiewicza 30, 30-059 Krakow, Poland
[b] Department of Mining Areas Protection, Geoinformatics and Mining Surveying, AGH University of Science and Technology, al. A. Mickiewicza 30, 30-059 Krakow, Poland

ARTICLE INFO

Article history:
Received 11 April 2022
Received in revised form 29 June 2022
Accepted 9 July 2022

Keywords:
Lava cave
Lava tube
Iceland
Arctic
Spatial impulse response
Climate changes

ABSTRACT

Lava caves are a broad group of caves formed by various volcanic processes. These unique and spectacular wonders of nature have a very surprising acoustic climate that can be described as very dry and intimate in comparison with the acoustics of typical rock caves. The paper shows the results of over 70 spatial impulse measurements in three different lava tubes located in west and southwest Iceland. The basic room acoustic parameters and Sound Pressure Levels were measured or calculated together with parametric statistical analysis. Moreover, laser scanning of the cave's geometry was conducted. The obtained reverberation time varies from 0.1 to 0.9 s for medium frequencies and up to 2 s for low ones and is similar in all three measured lava tubes. The performed measurements and analyses showed that materials and structures similar to those found in lava tubes could be used as sound absorbing equipment in concert halls or seminar rooms. The obtained spatial impulse responses, geometrical and structural data and the performed calculations can also be used in virtual reality systems or utilized while monitoring morphology, erosion progression and even microbiological activity in future.

1. Introduction

Subpolar and polar regions have a special place in the research activities that deal with climate change, including geology, biology and hydrology [1]. In recent years, the authors of the current paper started a series of investigations related to the acoustics of these areas [2], especially focusing on soundscape analysis [3] and noise management [4]. As an important part of the research, analysis of remarkable natural closed spaces – the glacier caves of Svalbard Archipelago – was performed [5]. Lava caves are the second point of interest in the Arctic region for our research team since they are the second most common type of natural interior in the subpolar regions. Additionally, we could not find any previous research about the acoustics of these structures. The current paper's goals are to perform a complex analysis of lava caves in Iceland, which is an original contribution to the conservation and monitoring of polar acoustics for future generations. The paper shows the current state of the acoustic climate and reverberation of the volcanic derived corridors. Most of the places where the research was performed are very remote and difficult to reach since there are no roads or even hiking trails to some caves. This is the reason the measurements were difficult to perform and some of the equipment had to be reduced or adjusted for these special circumstances. There were also problems with low temperature, power supply and limited time due to logistics.

In general, there is little research on the acoustics of polar regions, and most of it is concerned with hydroacoustics. For example, there is monitoring of infrasounds near a seismic station, located 4 km from Barentsburg on Spitsbergen, to compare the seismic signals with the acoustic waves coming from the glaciers [6]. One paper [7] presents the results of measurements of noise in an underwater environment, which were conducted in 2009 in Hornsund, Spitsbergen, surrounded by melting glaciers. Deane et al. [8] measured the directionality of ambient noise in an Arctic tidewater glacier bay using two horizontally spaced, broadband hydrophones. Another research program [9] was interested in the soundscape of the shallow water of the Arctic (Kongsfjorden, Svalbard). Other papers [10,11] present the analysis of noise data recorded by the Autonomous Hydroacoustic System (AHS) deployed in the Spitsbergen fjord, close to a colony of little auks. It focuses on the sounds generated by these small Arctic birds diving for food.

Volcanic explosion, lava effusion and various volcanic processes can create different types of lava caves [12]. A lava tube is defined as the most common type of lava cave. It is a form of tunnel near the subsurface formed of hardened lava [13]. The lengths of lava tube caves vary from a few meters up to several tens of kilometers.

* Corresponding author.
E-mail address: pawel.malecki@agh.edu.pl (P. Małecki).

https://doi.org/10.1016/j.apacoust.2022.108929
0003-682X/© 2022 The Authors. Published by Elsevier Ltd.

Their width and height vary from 0.5 m up to 20 m. Lava tubes can be found in several locations worldwide, including the most popular and studied ones in Hawaii, North America, Canary Islands, Azores, Mount Etna, the Middle East, Japan, South Korea, Galápagos, Easter Island, East Africa and Iceland, where lava caves coexist together with glacier caves. Moreover, ice structures are very common inside lava tubes in Iceland as well. Lava tubes in Iceland are the subject not only of geological research, but also of biology [13], history [14,15] and are even literary inspiration for famous writers such as Jules Verne [16].

The second paragraph of the paper describes the morphology and locations of the measured lava tubes. The third section explains the simplified measurement methods due to the difficult logistics of the polar environment. The next paragraph shows the obtained results together with the basic parametric statistical analysis. The fifth section provides an additional analysis of the relation between the reverberation time and the measurement point location. The article is summarized in the last section together with some insights and future work.

2. The cave morphology, localization and measurement timespan

The first reconnaissance and the preliminary acoustic measurements of lava tubes in Iceland were carried out in February 2018 in the Surtshellir (SU) cave. The second (main) examination together with laser scanning of the cave's geometry took place in March 2019. The SU cave was measured for the second time together with the Leidarendi (LE) and Vatnshellir (VA) caves. The location of the examined ice caves is shown in Fig. 1.

Laser scanning was performed with a Leica BLK 360 [20] panoramic scanner. It is an ultra-light, compact scanner, weighing only 1 kg, which is essential for cave measurements, as is the high-speed full sphere scanning within 3 min. This allows researchers to obtain up to 360,000 points per second with a very high resolution, obtaining the coordinates of the points together with RGB information. The accuracy of determining spatial coordinates is characterized by the value of 8 mm / 20 m. Measurements at individual stations could be combined in real time using dedicated software in a tablet, but, for safety reasons, it was decided to perform measurements with direct data recording in the device. These observations were then processed in the so-called post-processing, obtaining a uniform point cloud using the *Leica Cyclone Register 360* software. Such a cloud is characterized by an accuracy of about 50 mm in the absolute position, which is enough to recreate the correct geometric relations of the caves. The device's essential parameters are listed in Table 1.

The laser scans enable the collection of accurate geometrical data and later estimation of the wall's sound absorption. In addition, the obtained geometry records the current state of the corridors, which are subject to change because of natural erosion. The obtained floor and wall surfaces together with cave volumes are essential for future comparative studies on acoustical and geological research of the lava caves.

The Surtshellir Lava Cave System is located in the Hallmundarhraun lava field in the Borgarfjordur district of West Iceland. The name Surtshellir means, variously, the "Black Cave" or the "Cave of Surtur", a powerful fire giant according to Norse mythology. Surtshellir is mentioned several times in Icelandic medieval literature and seems to have been well-known as a threatening place, inhabited by giants or outlaws [15–17]. The Surtshellir system consists of three parts, Surtshellir - Stefánshellir – Íshellir, with a length of 3.5 km. Since the cave is located far from settlements or maintained roads, the entries are not easy to locate and access. Fig. 2 a and b show the entry covered by a snowdrift. All three caves are parts of one lava tube, formed by the same lava flow. At some locations the roof collapsed completely and thus left three pieces, which are not connected any more. The cave was used as a hideout by outlaws and bandits who would steal sheep from farmers living in the area in the 10th century. Surtshellir was explored and described first by Þorkell Arngrimsson in 1675. From then on, until the end of the 19th century, it was the longest known lava tube in the world. It is the longest lava tube in Iceland, about 1970 m long and the height varies throughout from 2 m to 10 m. The tunnels are around 15 m broad at their greatest width. Due to its volcanic origin, the walls are layers of solidified magma and basalt (Fig. 2 c-d) and the floors are covered with sheets of ice in the winter and large fallen rocks and lava rocks once the ice melts in the summer (Fig. 2 b-d).

The measured volume of the Surtshellir cave is around 56 000 m^3, the floor surface around 10 500 m^2 and corridor length of around 890 m. The laser scan of the Surtshellir cave is shown in Fig. 3.

The Vatnshellir cave is situated in the Snæfellsjökull National Park and is very popular with visitors and therefore has a well-maintained entrance, as shown in Fig. 4 a. The Vatnshellir cave was probably created in an eruption 6,000–8,000 years ago. The length of the cave is about 200 m and goes 35 m below the surface. Inside the lava cave there are two main sections. The upper section has great features and unique formations of lava statues curved on the sides of the lava tube. In the lower part of the lava cavern, which can be reached by a long and narrow staircase (Fig. 4 b), there are some rainbow-colored volcanic rocks and petrified lava formations (Fig. 4 c-d). The Vatnshellir lava tube cave inspired Jules Verne to write the science fiction novel Journey to the Center of the Earth [18].

The volume of the Vatnshellir cave is around 9 180 m^3, the floor surface around 1 100 m^2 and corridor length of around 140 m. The laser scan of the Vatnshellir cave is shown in Fig. 5.

Leiðarendi is a lava tube located in a lava field close to Bláfjöll, the Blue Mountains, in southwest Iceland (Figs. 1 and 6 a). Leiðarendi is, in fact, two caves, formed by two separate eruptions on the explosive Reykjanes Peninsula, the first one two thousand years ago, the second one a thousand years ago. A distinctive feature of Leiðarendi is the various lava flakes that have fallen from its walls and roof, due to frost and erosion (Fig. 6 b-c). These flakes indicate the many different lava streams that have flowed there subsequently throughout the ages. In the cave, there are also cave walls polished by lava streams along with stalagmites, stalactites and other formations, as shown in Fig. 6 d.

The measured volume of the Leiðarendi cave is around 12 300 m^3, the floor surface around 2 000 m^2 and corridor length of around 260 m. The laser scan of the Leiðarendi cave is shown in Fig. 7.

3. Acoustic measuring methods

Calculations of the acoustic parameters of selected caves were made using EASERA [21] software and scripts in MATLAB. There is a great deal of literature about the acoustics of concert halls and similar rooms for music and speech which is summarized in ISO 3382 standards [22]. For non-standard rooms, such as coupled rooms, unroofed or semi-open spaces, such as caves, the calculation of decay curves and reverberation times may be ambiguous, but most relevant research characterizes their acoustics using impulse response and derived parameters in accordance with the protocol of the ISO 3382 standard [23–26]. These are the arguments for performing measurements in caves following the ISO 3382 standard [22] as closely as possible, but, due to the specificity

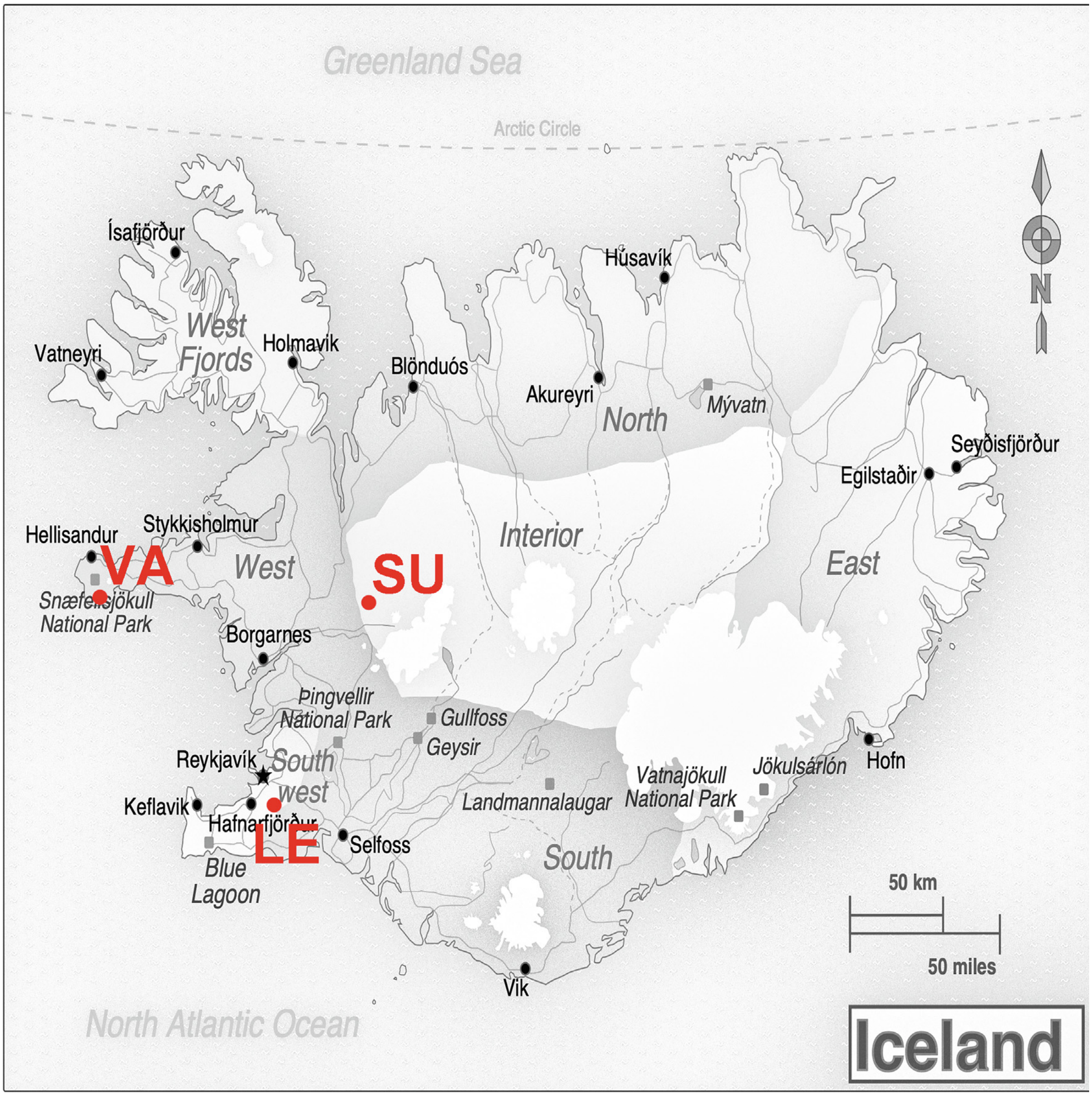

Fig. 1. Location of caves where the acoustic measurements were made [19].

Table 1
Technical specifications extracted from the datasheet of the laser scanner by its manufacturer [20].

Weight	1 kg
Dimensions	165/100 mm
Measurement speed	< 3 min for complete fulldome scan
Range	0,6–60 m
3D point accuracy	6 mm @ 10 m/6 mm @ 20 m
Point measurement rate	up to 360′000 pts/*sec*
Other	Spherical vision and thermal camera

of the space and logistic constraints, some simplifications were made.

Instead of a normalized omnidirectional sound source, an Ultimate Ears BOOM 2 [27] (portable, commercial sound source) was used. The parameters of Ultimate Ears BOOM 2 have been previously tested [28] in the AGH UST anechoic chamber [29] and used during the exploration of glacier caves [5]. The frequency response of the sound source is available in [5] and its usefulness in room parameters was proven in experimental measurements of large room (University corridor) acoustic parameters using a standard omni-directional source, a set of balloons and a directional, full-range studio monitor. Comparison of the obtained results using the standard omni-directional source and Ultimate Ears BOOM 2 showed minor differences between them. On the basis of that experiment's results and after measurements in an anechoic chamber [28], we decided to use this source in the cave measurements.

As a measuring microphone, a first-order Soundfield SPS 200 [30] ambisonic microphone was used to determine the spatial features of the sound field and to later use the recorded impulse responses for multi-channel auralization. The essential parameters of the employed acoustic instruments are listed in Table 2.

All the devices were packed in reduced soft cases, together with spare clothes, food and snow-ice tracking equipment, such as ropes and crampons etc. Basic acoustic parameters were calculated on the basis of a pressure signal from an ambisonic microphone (component W of B-format), whose frequency response was previously measured. In the acoustic range, its characteristic is linear with a deviation of not more than ± 3 dB. Test signals (10-second logarithm sine sweep) were recorded using a ZOOM H6 portable sound

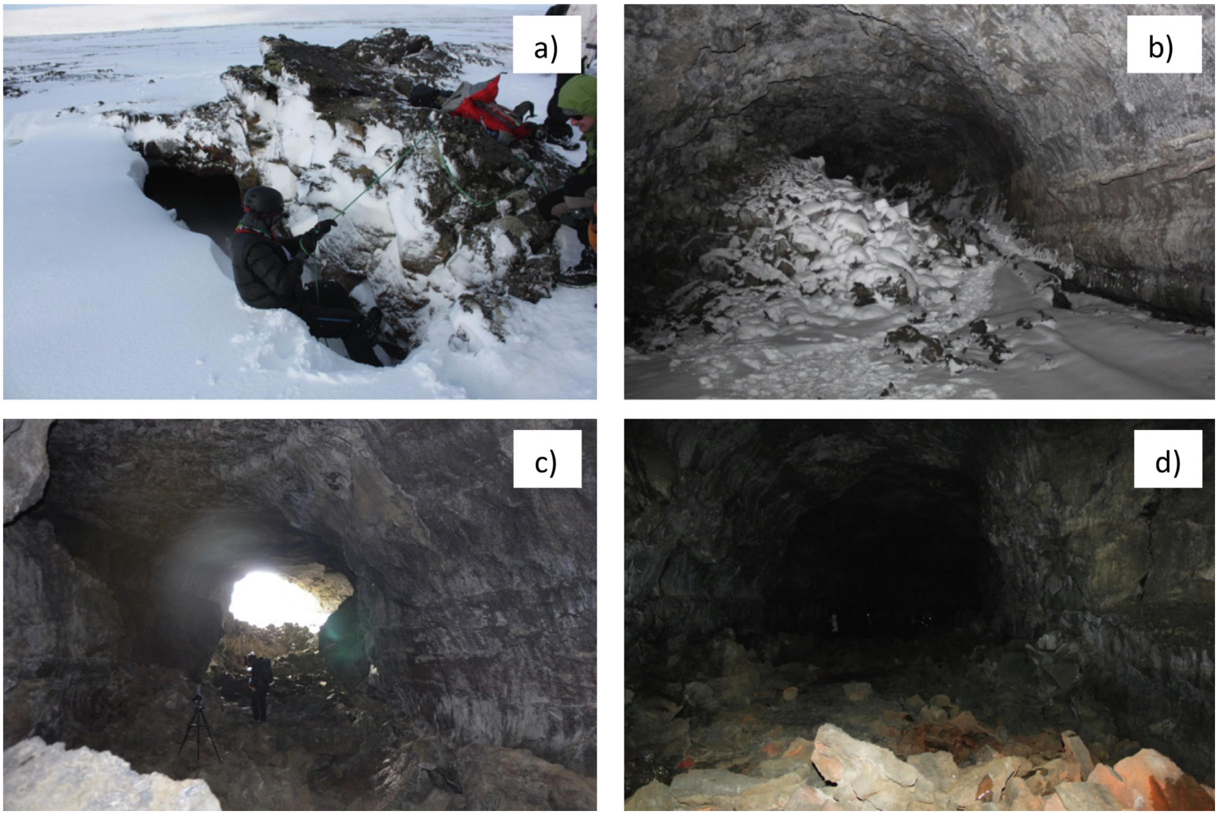

Fig. 2. Surtshellir (SU) morphology and appearance: a) cave entry, b-c) corridor begging, d) inside the tube.

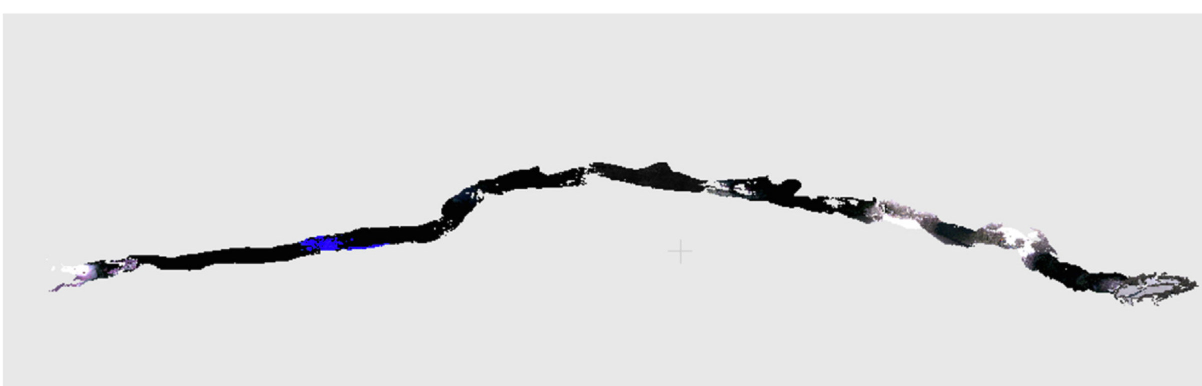

Fig. 3. Surtshellir (SU) laser scan outline.

recorder [31]. The signals were recorded with 24-bit resolution and a sampling frequency of 44.1 kHz.

In addition, the background sounds and sound pressure level generated during the determination of the impulse response were recorded during the measurements. A SVAN 959 sound analyser equipped with a ½'' 40AE free field microphone by G.R.A.S. and an SV12L microphone preamplifier was used in order to measure noise levels.

Due to the minimization and limitations of the measuring apparatus, the output test signal was recorded without synchronization with an input test signal (separate playback and recording devices were used). In order to calculate acoustic estimators, the impulse response h was calculated by deconvolution of the test signal s, which was a 10 s logarithmic sine sweep (1) where s_T is the test signal recorded in ice caves.

$$h(n) = F^{-1}\left[\frac{s_T(f)}{s(f)}\right] \quad (1)$$

4. Results and discussion

The main goal of the work is the complex analysis of the acoustic environment inside lava caves. Additional goals were to find the variability, dispersion, range or other possible statistical estimators of acoustic properties measured and calculated during the

Fig. 4. Vatnshellir (VA) morphology and appearance: a) cave entry, b) staircase between the caves, c-d) corridors.

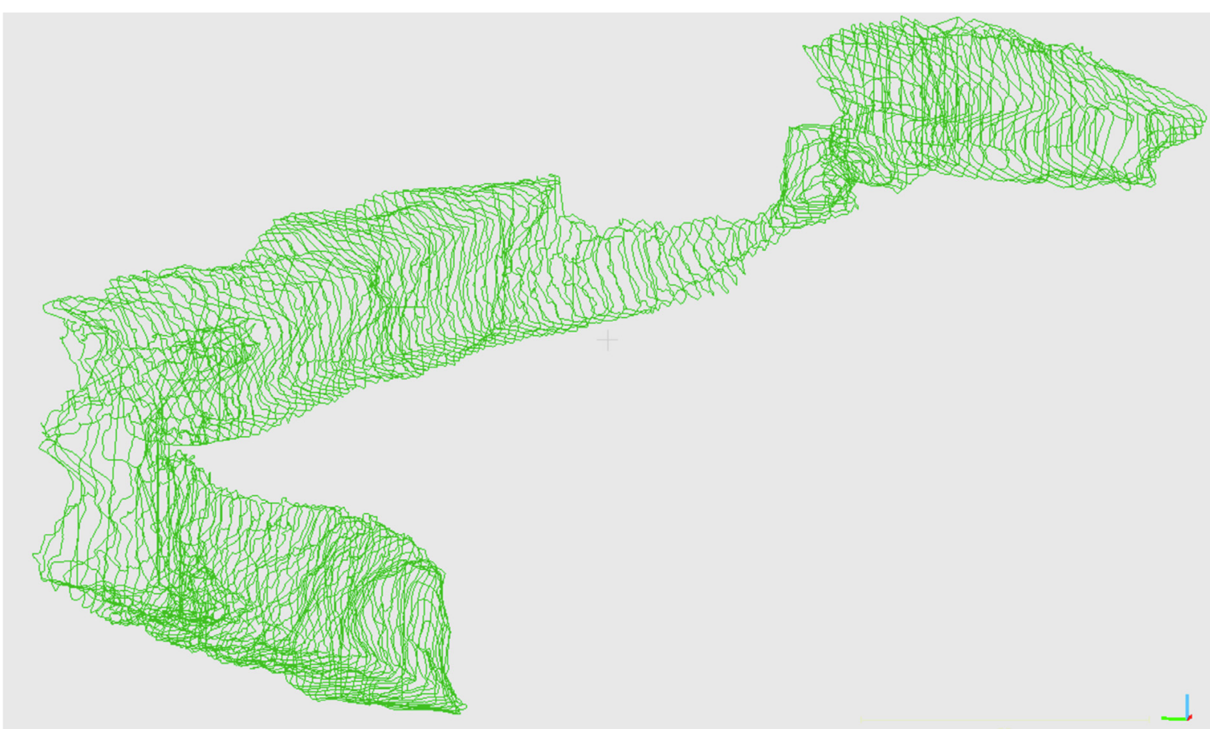

Fig. 5. Vatnshellir (VA) laser scan outline.

research. In order to achieve that, basic room acoustic estimators were calculated, such as: reverberation time, Early Decay Time (EDT), Bass Ratio (BR), Treble Ratio (TR), Clarity for Speech and Music (C7, C50 and C80), Sound Definition (D) and Speech Transmission Index (STI). All the parameters were calculated according to the ISO 3382 standard [22] using EASERA software [21].

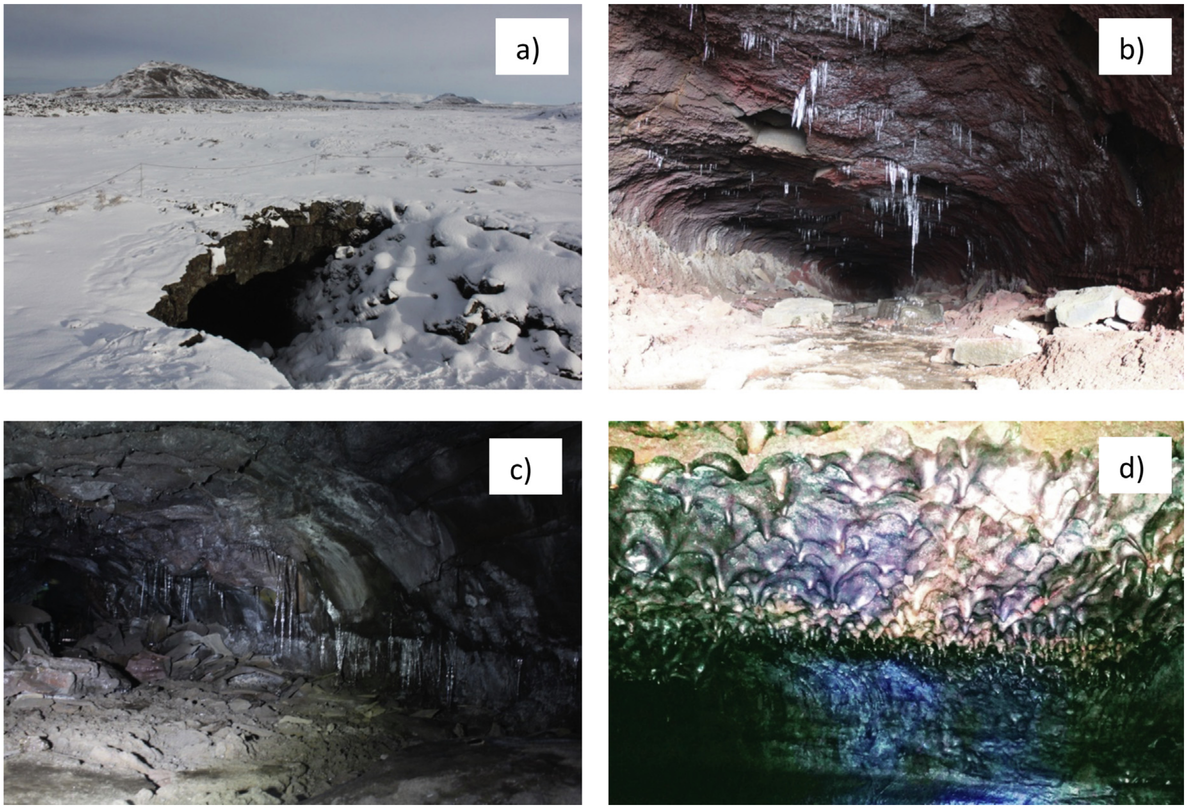

Fig. 6. Leiðarendi (LE) morphology and appearance: a) cave entrance, b-c) corridors, d) lava stalactites.

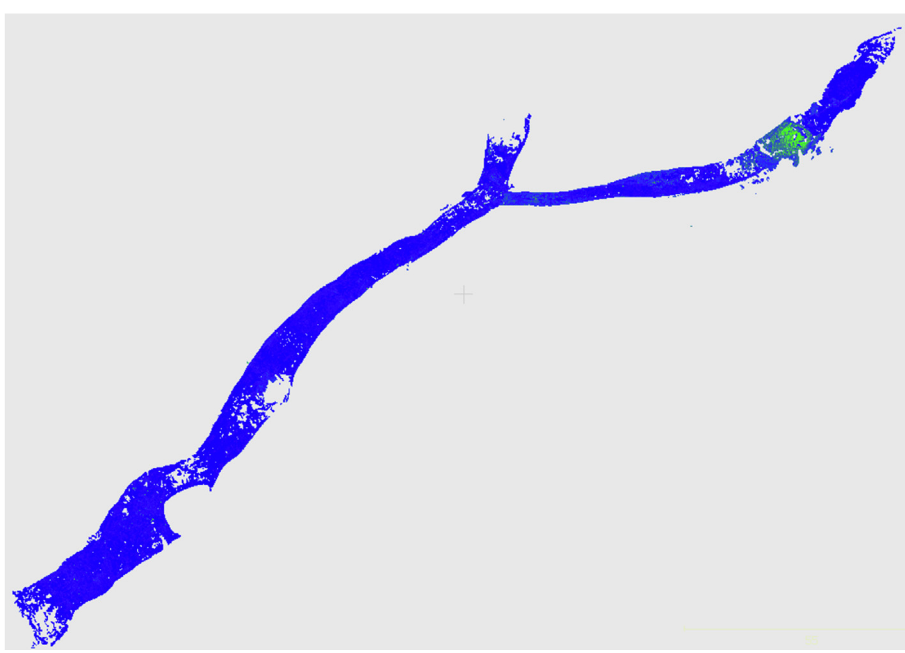

Fig. 7. Leiðarendi (LE) laser scan outline.

There were around 77 impulse responses measured in total in three lava caves. The number of measurement points in each cave depended on its length and morphology complexity, so the distance between subsequent points varied from about 5 to 20 m. Basic room acoustic estimators were calculated, such as: reverberation time, Early Decay Time (EDT), Bass Ratio (BR), Treble Ratio (TR), Clarity for Speech and Music (C7, C50 and C80), Sound Definition (D) and Speech Transmission Index (STI). All the parameters were calculated according to the ISO 3382 standard [22] using EASERA software [21].

Table 2
Technical Specifications of the employed acoustic instruments extracted from the datasheets provided by manufacturers [27,30,31].

	Soundfield SPS 200	Ultimate Ears BOOM 2	ZOOM H6
Frequency response [Hz]	40–20000	90–20000	1–48000
Sensitivity	14 mV/Pa	–	–
S/N Ratio [dB]	82	–	–
Self noise	12 dB DIN/IEC	–	−120 dBu
Max input	120 SPL [dBA]	90	22 dBu
Directivity	Ambisonics A-format	Omnidirectional	–
Other		IPX7	Input gain 55 dB

4.1. Reverberation time

Generally, lava tubes reverberation could be described as short or medium. Fig. 8 a, c and e show the T20 reverberation time as a function of frequency at all points of the caves under study, while Fig. 8 b, d and e show the Early Decay Time in an analogical way. The highest variation of the results is observed for low frequencies. Above approx. 300 Hz the obtained values are quite consistent for most of the measuring points. The medians of individual values are marked in bold. Fig. 9 shows the parametric statistical distribution EDT (average of 500 and 1000 Hz octave bands) and reverberation time calculated using various methods (T10, T20 and T30: average of 500 and 1000 Hz).

The reverberation time of the studied caves varies from 0.1 to 0.9 s. The lowest values of reverberation time and EDT, as well as their smallest variability, are observed for the LE cave. The median EDT is about 0.2 s, and for T20 about 0.25 s. On the other hand, the SU cave has the greatest variability. The median EDT is about 0.45 s and for T20 about 0.55 s. Maximum values oscillate within 0.9-second limits. The frequency characteristics in the low frequency range are a little more diverse and have different local extremes for each measurement point. It can be concluded that there is a dominance of wave phenomena at resonance frequencies and a stochastic nature of the sound field at medium and high frequencies. In all cases, EDT values are a little bit lower in general but more disperse.

4.2. Timbre parameters, clarity and intelligibility of speech

In terms of timbre, all the examined ice caves are quite similar (Fig. 10). The median of the BR bass indicator is in the range of 0.9–1.2 with moderate variation of the results. The TR high tones parameter varies from 0.8 to 1.1 with very small variation of the results. Therefore, it can be stated that lava tube acoustics are quite different from the typical 'image' of caves mostly associated with dark and long reverberation.

On the other hand, the sound clarity is relatively low and variable (Fig. 11). For the LE and SU caves, median clarity values are quite similar, but for LE they are also very close to low statistical estimators (minimum and 25th percentile). For the VA cave, it is the opposite – the median values are close to high statistical estimators (maximum and 75th percentile). In addition, the VA median values are higher than for the other caves – around 5 dB for C50 and C80 while SU and LE are close to −10 dB.

Fig. 12 shows the selectivity of D and the intelligibility of STI sound. By definition, the parameter D is strongly correlated with C50, so the distribution of results is also very similar. Speech intelligibility can be described as excellent for all the examined caves. The calculations of sound clarity C and sound definition D in Figs. 11 and 12 are calculated for broadband impulse response without filtering.

4.3. Sound pressure level

Most of the lava caves where the measurements were made are far from human settlements and communication routes. Hence, the background noise levels measured in the SU and LE caves are very low, on the limit of the internal noise level of the sound level meter (SLM). In the case of the used SLM it was 13 dB (A) (measured at the AGH University of Science and Technology and declared by the manufacturer) [32].). In the Vatnshellir cave, falling water drops raised the acoustic background level to the value of 34–37 dB SPL(A). Since the measurement signals were about 65 to 70 dB SPL(A), background noise levels had no effect on the measured impulse responses. It should be noted that all the acoustic measurements were taken in the absence of other people whose presence would have an impact on the level of the background noise.

4.4. Relation of measurement location and reverberation time

Since the accurate geometry of the measured caves was captured by laser scanning, the next step of research is estimation of the average sound absorption and its variability in accordance with the geometrical and structural data. In the current work, the relation of measurement location and the reverberation time is provided in Fig. 13, which shows compiled data for all three caves. In the SU cave, the first 12 measurements were taken in the corridor from the entry to the blocked area by the fallen stones, which can be defined as a single volume. The measurements from 13 to 18 were taken in the second volume of a very diverse structure due to the many fallen rocks. Measurements 21 to 26 were taken in the fourth separate volume called Stephan, with the cross-section becoming smaller with every measuring spot.

The first two measurements in the VA cave were taken in the first, smaller volume. For measurements 3 to 11, the spots were uniformly distributed from the stairs to the biggest volume, where the last 4 impulse responses were captured. The LE cave was the smallest in terms of average width and height and the first 9 measurements were taken in a quite constant volume, while measurements 10 to 17 were taken in a broader period.

4.5. Discussion

There are several factors that must be taken into account before making any general conclusions or comments about the performed research. The caves are natural creations and their geometry or other properties are the results of the very complex phenomena of different origins. The work covers only a small fraction of the possible lava tubes in the world or even in Iceland. Their possible age, surrounding climate, and human activities are factors that may influence the acoustic environment inside other caves. The other problem is to establish the influence of the cave entries or any other existing holes on the measurements. The same problem exists for any semi-open spaces, like railway stations, but in these cases the simulations can be much easier since the geometry and material sound absorption is well known. For caves or other natural creations, it is not so obvious, so the accurate scanning of the geometry together with accurate RGB information and resulting sound absorption could be potential material for theoretical or numerical analysis of the sound propagation. The other possible problem is the estimation of source-receiver distance sensitive parameters, like STI.

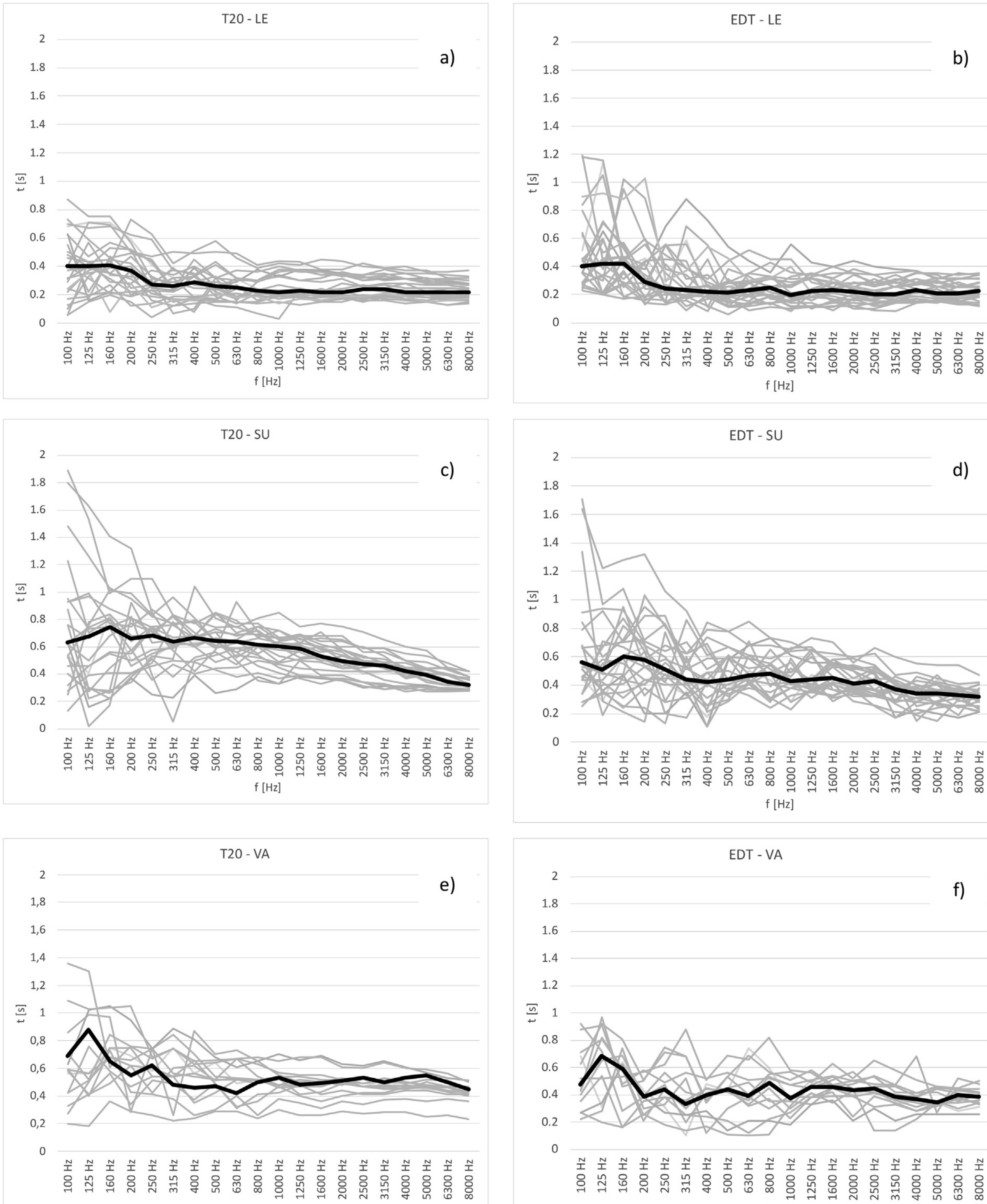

Fig. 8. T20 reverberation time and Early Decay Time in the: a-b) LE, c-d) SU and e-f) VA caves; the solid lines show the median values, dashed lines show 1st and 3rd quartiles and the outliers are marked with crosses (old: Fig. 8. T20 reverberation time and Early Decay Time in the: a-b) LE, c-d) SU and e-f) VA caves; thin, gray lines show results from individual measurement points, and the bold black line shows the median values).

Because of the difficult circumstances, the distance between the microphone and loudspeaker was not monitored carefully as it was a result of the obstacles and geometry variability. Despite that, the STI results (Fig. 12) show minor dispersion and high values due to the quite high sound absorption, very high dispersion and low noise level.

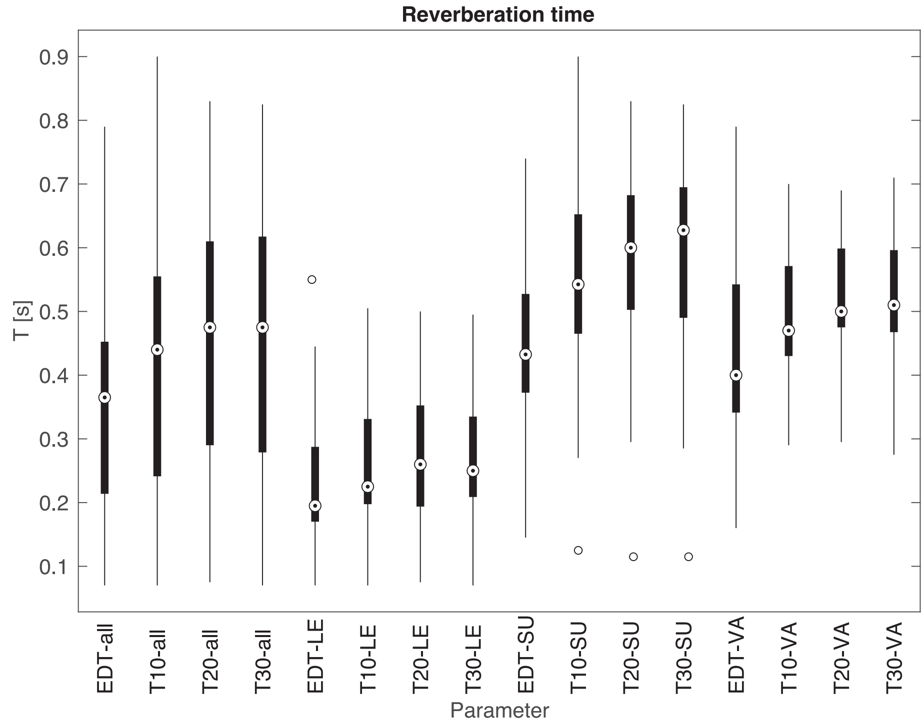

Fig. 9. Box chart of reverberation time distribution of T10, T20, T30 and early decay time (EDT) of the studied caves.

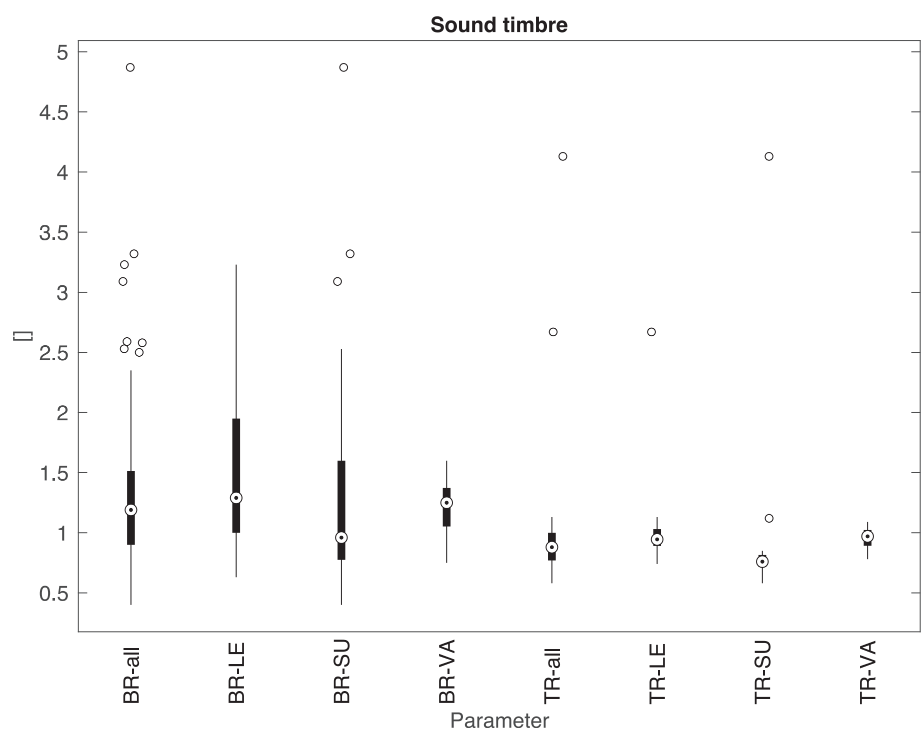

Fig. 10. Box chart of the distribution of the BR bass factor and high tones TR of the examined caves.

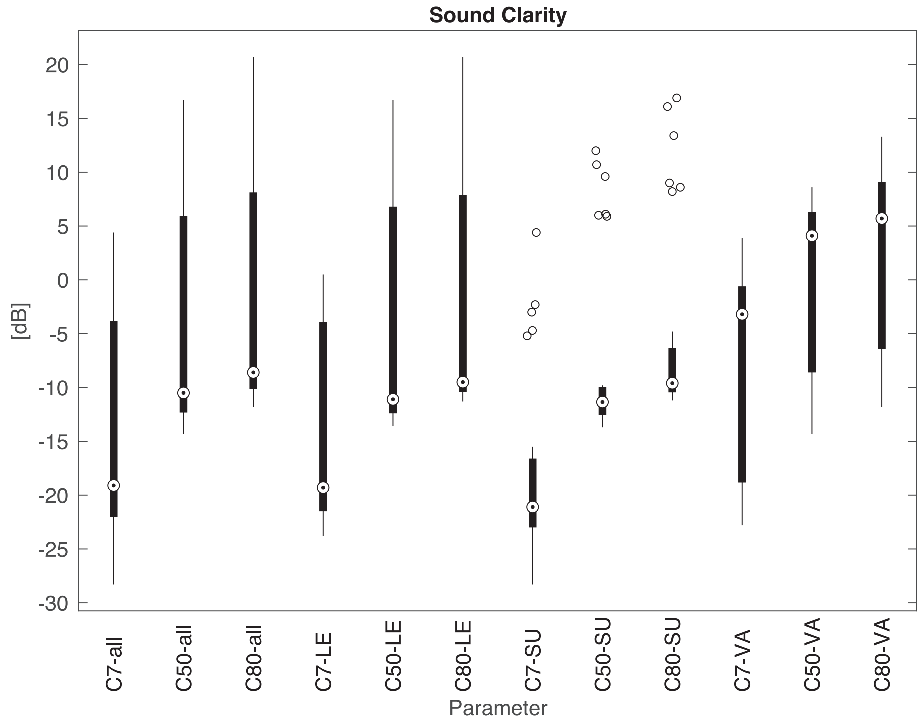

Fig. 11. Box chart of the distribution of C7 sound clarity, sound clarity for C50 speech and C80 music of the studied caves.

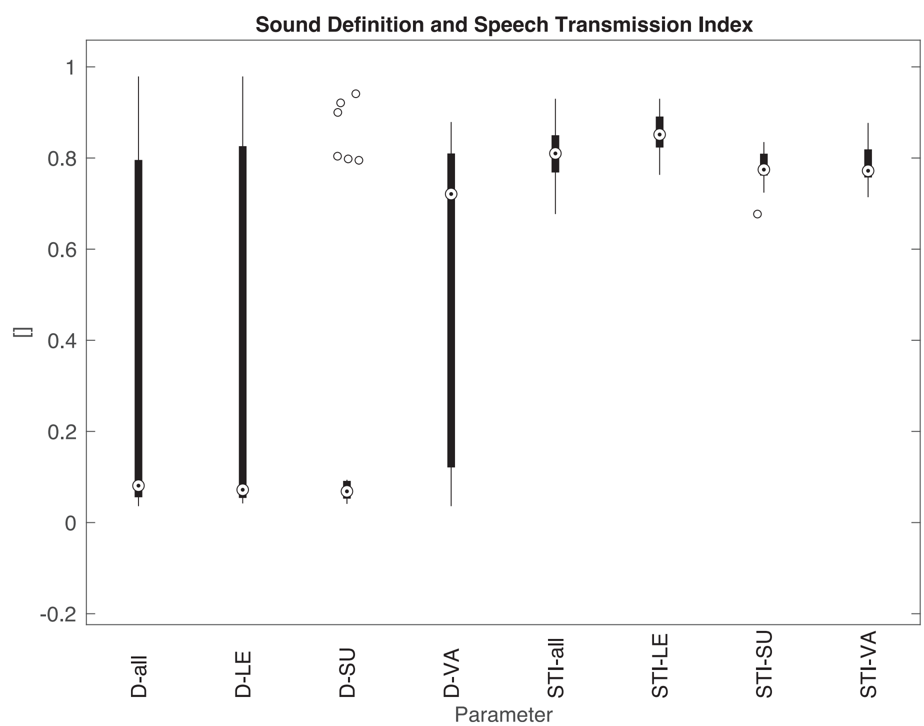

Fig. 12. Box chart of the sound definition distribution D and the STI speech intelligibility index of the studied caves.

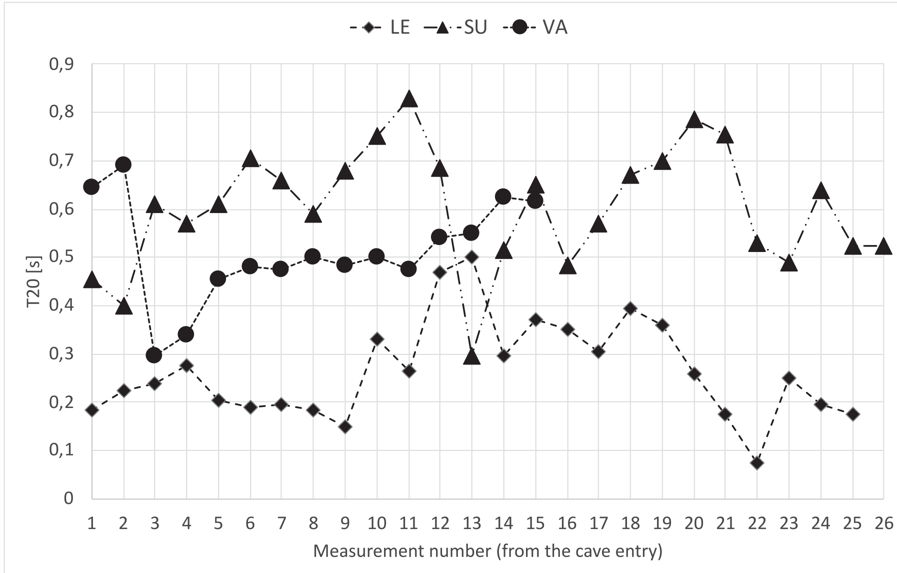

Fig. 13. T20 reverberation time (average for 500 and 1000 Hz) in the measured caves with measurement order.

5. Summary and conclusions

The acoustic measurements of three different lava tubes in Iceland have shown the general similarity of reverberation time and most of the other acoustic parameters. The reverberation time varies from 0.1 to 0.9 s for medium frequencies and up to 2 s for low ones. Early Decay Time values are generally lower than T10, T20 or T30. In comparison with the stone caves investigated in [33], and previously studied glacier caves [5], lava tubes can be described as very dry and intimate in the sense of acoustics and sound propagation inside these structures. Therefore, such surfaces, stone density and surface structure could be used in modern concert halls or similar venues where sound absorption is generally desired. This kind of approach was already utilized after previous similar research [5] for the design of acoustic panels [34] inspired by nature. So, the next step of the current research is to perform a calculation of the absorption coefficient of the lava caves.

The performed calculations and analysis can also be utilized while monitoring morphology, erosion progression and even microbiological activity in a long-term scale. The obtained results are to be a reference point for future activities in that field. The obtained spatial impulse responses can also be used in virtual reality systems or multimedia applications in order to recreate the character of this kind of unique space. Impulse responses from glacier caves [5] are to be used in the planetarium show called *Living World* by the California Academy of Sciences, so it is the next potential outcome of the results of the current work.

CRediT authorship contribution statement

Paweł Małecki: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Tomasz Lipecki:** Methodology, Investigation. **Dorota Czopek:** Investigation, Data curation, Funding acquisition. **Janusz Piechowicz:** Investigation. **Jerzy Wiciak:** Conceptualization, Investigation, Writing – review & editing, Supervision, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pawel Malecki, Tomasz Lipecki, Dorota Czopek, Janusz Piechowicz, Jerzy Wiciak report administrative support was provided by The Environment Agency in Iceland.

Acknowledgments

This research has been partially supported by the project: No. 16.16.130.942. The research was conducted thanks to permit no. UST201902-274/Þ.V.B. issued by The Environment Agency in Iceland.

References

[1] Polish Polar Research, https://journals.pan.pl/ppr, accessed: 15 June 2022.
[2] Czopek D, Małecki P, Piechowicz J, Wiciak J. Acoustic environment of Spitsbergen : selected issues. Kraków: Wydawnictwo AGH; 2018 (in polish).
[3] Czopek D, Małecki P, Piechowicz J, Wiciak J. Soundscape analysis of selected landforms on Spitsbergen. Arch Acoustics 2019;44(3):511–9. https://doi.org/10.24425/aoa.2019.129266.
[4] Piechowicz J, Wiciak J, Czopek D, Malecki P. Noise in the arctic settlements, IEEE Xplore. Joint Conf – Acoust 2018:1–6. https://doi.org/10.1109/ACOUSTICS.2018.8502406.
[5] Małecki P, Czopek D, Piechowicz J, Wiciak J. Acoustic analysis of the glacier caves in Svalbard. Appl Acoust 2020;165. https://doi.org/10.1016/j.apacoust.2020.107300.
[6] Vinogradov Y, Kremenetskaya E. Infrasound research in Spitsbergen. Geophys Res Abstracts 2013;15(EGU2013):4590.
[7] Tegowski J, Deane GB, Lisimenka A, Blondel Ph. Spectral and statistical analyses of ambient noise in Spitsbergen fjords and identification of glacier calving events. In: Proceedings of the 11th European conference on underwater acoustics. p. 1667–72.
[8] Deane GB, Głowacki O, Tegowski J, Moskalik M, Blondel F. Directionality of the ambient noise field in an Arctic, glacial bay. J. Acoust. Soc. Am. 2014;136: EL350–6. https://doi.org/10.1121/1.4897354.
[9] Buscaino G., Filiciotto F., Maccarrone V., Di Stefano V., Mazzola S. The soundscape of the shallow water of Artic sea (Kongsfjorden, Svalbard): preliminary results. Proceedings of The 2014 US-IALE Annual Symposium, Anchorage.
[10] Szczucka J., Acoustic studies of diving birds in the Arctic, 3rd International Conference on Underwater Acoustic Measurements:Technologies & Results, Nafplion, Greece, 2009, pp.1181–1188.
[11] Szczucka J. Noise of diving arctic birds. Hydroacoustics 2011;14:229–36.
[12] Sawłowicz Z. A short review of pyroducts (lava tubes). In Annales Societatis Geologorum Poloniae 2020;90(4). https://doi.org/10.14241/asgp.2020.34.

[13] Gadányi P., van der Bogert C.H. Lava Tube. In: Encyclopedia of Planetary Landforms. Springer, New York, 2014. NY. 10.1007/978-1-4614-9213-9_474-1.
[14] Halliday WR. Volcanic caves. In: Gunn J, editor. Encyclopedia of caves and Karst science. New York: Fitzroy Dearborn; 2004. p. 761–4. 10.1016/j.apacoust.2020.107300.
[15] Northup DE, Stefánsson ÁB, Medina MJ, Caimi NA, Kooser AS. Microbial communities of Icelandic lava caves. Proc. of the 16th Int Symp Vulcanospeleo 2016, Ocean View, HI, 2016.
[16] Ólafsson G, Smith KP, McGovern T. Surtshellir: a fortified outlaw cave in West Iceland. In The Viking Age: Ireland and the West. In: Papers from the Proceedings of the Fifteenth Viking Congress, Cork, 18-27 August 2005. p. 283–97.
[17] Stefánsson ÁB, Stefánsdóttr G. Surtshellir in Hallmundarhraun. Historical overview, exploration, memories, damage, an attempt to reconstruct its glorious past. NSS News 2016;74(5):12–9.
[18] Stefánsson AB. The Vatnshellir Project, a first for Iceland. In: Proceedings of the 14th international symposium on vulcanospeleology. p. 115–21.
[19] https://commons.wikimedia.org/wiki/File:Iceland_Regions_map.svg, used under CC BY-SA 3.0, Desaturated from original, accessed: 15 June 2022.
[20] https://shop.leica-geosystems.com/leica-blk/blk360/product-details, accessed: 15 June 2022.
[21] AFMG Technologies GmbH. EASERA software information, https://easera.afmg.eu/, accessed: 27 March 2019.
[22] ISO EN 3382. Acoustics. Measurement of the reverberation time of rooms with reference to other acoustical parameters. 2012.
[23] Girón, S., Álvarez-Corbacho, Á. and Zamarreño, T. Exploring the acoustics of ancient open-air theatres, 2020, Arch Acoustics, 45. doi: 10.24425/aoa.2020.132494.
[24] Rindel JH. Roman theatres and revival of their acoustics in the ERATO project. Acta Acust United Acust 2013;99(1):21–9.
[25] Farnetani A, Prodi N, Pompoli R. On the acoustics of ancient Greek and Roman theaters. J Acoust Soc Am 2008;124(3):1557–67. https://doi.org/10.1121/1.2951604.
[26] Martellotta F, Cirillo E, Carbonari A, Ricciardi P. Guidelines for acoustical measurements in churches. Appl Acoust 2009;70(2):378–88. https://doi.org/10.1016/j.apacoust.2008.04.004.
[27] Ultimate Ears BOOM 2 specification. https://www.ultimateears.com/en-us/wireless-speakers/boom-2.html#diagram, accessed: 27 March 2019.
[28] Sochaczewska K, Wiciak J, Małecki P. Alternative sound sources in impulse response measurements of limited accessibility acoustic spaces (in Polish). Creativetime: Nowe wyzwania dla polskiej nauki; 2017.
[29] Pilch A., Kamisiński T. The effect of geometrical and material modification of sound diffusers on their acoustic parameters 2011, Arch Acoustics 36.4; 955-966.
[30] Soundfield SPS200 Software Controlled Microphone Owner's Manual: https://s3-us-west-2.amazonaws.com/cdn.soundfield.com/assets/downloads/manual/SPS200.pdf, accessed: 17 May 2019.
[31] ZOOM H6 Specification https://zoomcorp.com/en/de/handheld-recorders/handheld-recorders/h6-audio-recorder/, accessed: 18 May 2022.
[32] Wiciak J, Mleczko D, Ozga A, Wszolek G, Wierzbicki J, Piechowicz J, et al. Quietness in the Soundscape of the Bialowieza National Park. Act Phys Pol A 2014;125:99–102.
[33] Iannace G, Trematerra A. The acoustics of the caves. Appl acoust 2014;86:42–6.
[34] Czopek D, Małecki P, Piechowicz J, Wiciak J. The acoustics of ice caves in the Svalbard for the design of modern acoustic wall panels. Proceedings of the Svalbard science conference 5-6 November 2019, Oslo, 2019.