Acta Montanistica Slovaca Volume **20** (2015), number **2**, 156-163

Determination of dynamic Young's modulus of vulnerable speleothems

***Pavel Konečný*[1], *Markéta Lednická*[1], *Kamil Souček*[1], *Lubomír Staš*[1], *Lukáš Kubina*[1] and *Katalin Gribovszki*[2]**

Intact and vulnerable speleothems can be investigated in situ to estimate an upper limit of prehistoric peak ground acceleration. It is possible to say that intact speleothem was not loaded by horizontal acceleration higher than the value of horizontal acceleration resulting in failure, which is assessed by theoretical calculations. Mechanical properties of broken speleothems originating in the same cave are considered for this calculation.

In the present paper, determination of the dynamic Young's modulus of broken speleothems originated in Baradla-Domica cave system (Northern Hungary and Southern Slovakia) is presented. The dynamic Young's modulus can be calculated based on P and S-wave velocities and bulk density of tested specimens. Two different approaches to determination of bulk density of irregular speleothem specimens are presented - determination of bulk density by standard "Water displacement method" and by "X-Ray Computed Tomography".

Key words: *dynamic Young´s modulus, speleothem, bulk density, X-Ray Computed Tomography*

Introduction

Displaced and/or broken speleothems document among other things movements of fractures or vibrations in the given area (e.g. Forti, 2001, Becker et al., 2006, 2012, Šebela, 2008), so they can be used as a tool for tectonic and seismic analyses. However, not only broken speleothems serve for investigation of prehistoric earthquakes. Intact and vulnerable stalagmites are also investigated in situ to estimate an upper limit of prehistoric peak ground acceleration (e.g. Gribovszki et al., 2013a, Szeidovitz et al., 2008a, 2008b).

In situ testing of intact and vulnerable stalagmites and analysing broken speleothems using laboratory measurements enables to determine the maximum peak ground acceleration (PGA) resulting in its breaking. Using a theoretical calculation considering physical and mechanical parameters of broken speleothems, it is possible to determine PGA in the investigated area for time intervals comparable with the lifetime of investigated speleothems (i.e. of the order of 10.000 – 100.000 years). The obtained PGA values are of an importance because the earthquake catalogues are complete for the last several hundreds of years only in case of destructive events while the return period is of the order of some hundreds or even some thousands of years. It is possible to obtain some valuable information by this way for longer periods and consequently it is useful to make more realistic seismic hazard assessments (e.g. Lacave et al., 2012, Bokelmann and Gribovszki, 2015).

The principle of investigation of stalagmites is as follows:

- physical and mechanical parameters on fragments of broken speleothems are measured in laboratory conditions by both non-destructive and destructive testing methods such as density measurement, determination of Young´s modulus, tensile and compressive strength, P-wave and S-wave velocities, etc.;
- natural frequency on intact stalagmites is measured in situ by non-destructive methods;
- analytical calculations based on stalagmite´s shape (height and diameter) and its parameters are performed - theoretical natural frequency is calculated, and the maximum PGA during modelled breaking of stalagmite is determined;
- dating the stalagmite´s age is performed using core samples taken from different parts of stalagmite.

Determined physical and mechanical parameters of investigated speleothems significantly influence calculated values of PGA and theoretical natural frequency. Vulnerable intact stalagmites (high, slim and more or less cylindrical shape) are considered the beams working in breaking and loaded by a seismic motion at their fixing point. The dynamic Young's modulus, which is discussed in this paper, enters the formulae for computation of theoretical natural frequency of a cantilever beam (e.g. Cadorin et al., 2001):

---

[1] Ing., Dr .,*Pavel Konečný, Ing., Markéta Lednická, PhD., Ing., Kamil Souček, PhD., RNDr.Lubomír Staš, CSc., Ing. Lukáš Kubina*, Institute of Geonics of Czech Academy of Science, v.v.i., Studentská 1768, 708 00 Ostrava-Poruba, Czech Republic, pavel.konecny@ugn.cas.cz, marketa.lednicka@ugn.cas.cz, kamil.soucek@ugn.cas.cz, lubos.stas@ugn.cas.cz, lukas.kubina@ugn.cas.cz

[2] *Katalin Gribovszki, Dr*., Department of Meteorology and Geophysics, University of Vienna, UZA II, Althanstraße 14, 1090 Wien, Austria, gribovk2@univie.ac.at , Geodetic and Geophysical Institute, Research Centre for Astronomy and Earth Science, Hungarian Academy of Sciences, Csatkai Endre u. 6-8., H-9400 Sopron, Hungary, kgribovs@ggki.hu

$$f = \frac{1}{\pi}\sqrt{\frac{3ED^2}{16\rho H^4}} \qquad (1)$$

The parameters considered in the formulae are:
f – frequency (Hz),
E – dynamic Young´s modulus of the stalagmite (Pa),
D – diameter of the stalagmite (m),
ρ – bulk density of the stalagmite (kg/m^3),
H – height of the stalagmite (m).

The dynamic Young´s modulus can be calculated (e.g. Lama and Vutukuri, 1978; Barton, 2007):

$$E = \rho V_s^2 \; \frac{3(V_p/V_s)^2-4}{(V_p/V_s)^2-1} \qquad (2)$$

where:
E - dynamic Young’s modulus (Pa),
ρ - bulk density (kg/m^3),
v_p - P-wave velocity (m/s),
v_s - S-wave velocity (m/s).

The presented case study of the dynamic Young’s modulus determination was performed on two parts of broken slim speleothems originated in Čertova diera (Ördög-lik) hall of Domica cave. Parameters ρ, v_s and v_p needed for the dynamic Young’s modulus calculation were determined by laboratory non-destructive testing methods. These methods enable to determine selected parameters of tested specimens and to preserve them for other testing, e.g. measurement of failure stress in tension needed for calculation of ground acceleration that leads to the failure of stalagmite. Ultrasonic P and S-wave velocities were determined based on ultrasonic measurement by direct pulse transmission technique. The bulk density of irregular speleothem specimens was determined by two different methods – “Water displacement method” and “X-Ray Computed Tomography. The influence of the selected method on the resulting dynamic Young’s modulus is discussed in this study, and the best way of determination of dynamic Young’s modulus of vulnerable speleothem is suggested.

Speleothem specimens

As was mentioned above, the tested broken parts of speleothems originate from the Baradla-Domica cave system that is located at the border of Hungary and Slovakia. Several samples of broken speleothems from this cave system were tested in previous studies to determine PGA of this region (e.g. Szeidovitz, et al., 2008a; Gribovszki et al., 2013b).

Within presented study, two parts of slim speleothems (Fig. 1) were chosen for laboratory testing, that have a similar average diameter as the most vulnerable intact stalagmites investigated in situ in the cave with the average diameter approximately 50 mm. The length of tested speleothems was 183 and 189 mm respectively. During the laboratory measurement, it was necessary to preserve the specimens in their original irregular shape; they were cut and polished only at the sides to have an appropriate conditions for ultrasonic measurements.

Fig. 1 Tested specimens of broken speleothems.

Determination of P-wave and S-wave velocities

A digital ultrasonic portable instrument Pundit Lab+ (Proceq Company) was used for the measurement of P-wave (v_P) and S-wave (v_S) velocities by direct pulse transmission technique. Frequency of both used transducers was 250 kHz (P-wave transducers with the diameter d = 25 mm and S-wave transducers with the diameter d = 30 mm). The contact between the specimen and the transducers was improved using a thin layer of special couplant produced by the Proceq Company for the P-wave transducers and coupling paste of very high viscosity for the S-wave transducers. Before testing the speleothems, calibration of the system was carried out for each of used transducers using calibration rod produced by the manufacturer (the expected calibration value of travel time for the P-wave is marked on the calibration rod). Measurement was performed in the longitudinal direction of the stalagmite; it means that the transmission path corresponds to the length of the testing stalagmite sample. Transducers were coupled manually during the testing. According the ISRM suggested method (Aydin, 2015), the travel time should be measured at least three times applying different pressures when the transducers are coupled manually. During the P-wave velocity measurement, five measurements were performed using ten pulse intervals for each specimen. During the S-wave velocity measurement, five measurements were performed using 20 pulse intervals and using a different rotation of transducers. After the measurement, detailed picking off individual wave groups of recorded signals was performed using Punditlink software and corrected transmission times were used for calculation of P-wave and S-wave velocities. Mean and standard deviations of velocity variations were calculated for each specimen, and the results are presented in Tab. 1.

Tab. 1. Ultrasonic P-wave and S-wave velocities.

Specimen no.	**v_p** [m/s]		**v_s** [m/s]	
	mean	**standard deviation**	**mean**	**standard deviation**
14483	4551	56.3	2324	54.6
14484	4781	30.3	2389	22.9

Determination of bulk density

Bulk density is a crucial value for the determination of dynamic Young´s modulus, theoretical natural frequency of speleothem and the peak ground acceleration resulting in failure of a speleothem. The standard method of determination of bulk density of irregular specimens suggested by ISRM is "Water displacement method" (Franklin et al., 1979). The bulk volume of irregular specimens may be calculated using the Archimedes principle. The specimen is coated with wax, and its bulk volume is determined from the water volume displaced by the coated specimen, corrected for the volume of the coating material. The results of the bulk volume are presented in Tab. 2.

Tab. 2. Bulk density calculated by different methods.

Specimen no.	**Mass** [kg]	**Water displacement method**	**X-RAY CT method**	
		Bulk density [kg/m^3]	**Volume** [mm^3]	**Bulk density** [kg/m^3]
14483	0.58727	2323	250972.49	2334
14484	0.58822	2235	259940.02	2263

X-Ray Computed Tomography (CT) as an alternative method for volume determination

The application of the X-ray CT method for quantitative and qualitative analyses of the behaviour of different kinds of geomaterials and other related materials, such as rocks, soil, construction materials, ceramic materials and geocomposites is gradually increasing. The X-ray Computed Tomography (X-ray CT) represents not only a progressive non-destructive method of analysing the inner structure of materials. This method enables determination of volumes of irregularly shaped samples and different kind of the analysed objects too. For the determination of the total volume of the analysed broken stalagmites, the Nikon Metrology XT H 450 2D/3DST industrial micro X-ray CT system was used. It is a fully automated apparatus with a rotating scanning system equipped with micro focal X-ray source that generates cone-shaped beams (Sitek et al., 2015).

The technical specification is given in the Tab. 3. Studied volumes were reconstructed using the CT Pro 3D software (by Nikon Metrology NV).

Tab. 3. The basic technical specification of X-ray CT.

Max. acceleration voltage and power of the X-ray source (reflection mode)	450kV / 450W
Size of the X-ray focus spot at power of 200W	cc. 80 μm
Max. weight, diameter and height of scanned objects	100 kg / approx. 0.3 m / 0.3 m
Max. X-raying	395 kg/m^2
X-ray Detectors	
Flat panel (16-bit depth) – area detector 400x400 mm	200 μm per pixel, No. of pixels - 2000 x 2000
Linear curve detector (16-bit depth)	400 μm per pixel No. of pixels - 2 000

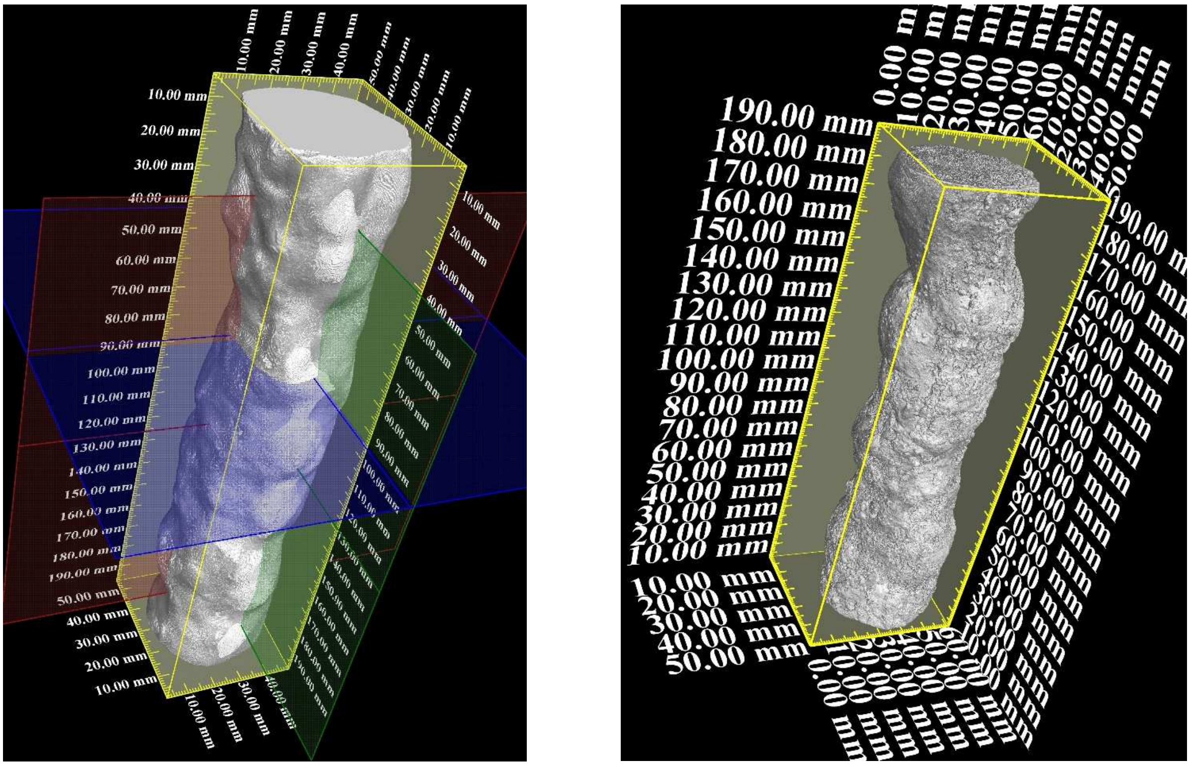
Settings of parameters of the micro X-ray CT system used for scanning of broken stalagmites are presented in detail in Tab. 4.

Tab. 4 Settings of parameters of micro X-Ray CT.

X-ray source settings	
X-ray penetration [kV]	220
X-ray Intensity [μA]	180
X-ray power	cc. 40W
X-ray filter	Copper, thickness 1mm
Settings of CT scanning	
No. of projections [--]	1600
No. of frames per projection [--]	2
Projection exposure [ms]	1415
Scanning time [h]	Approx 1.5
Reconstruction	
Voxel resolution [μm]	111
Reconstruction time [min]	up to 10 min.
Voxel type	cubic
Voxel bit depth / grey levels	8-bit / 255

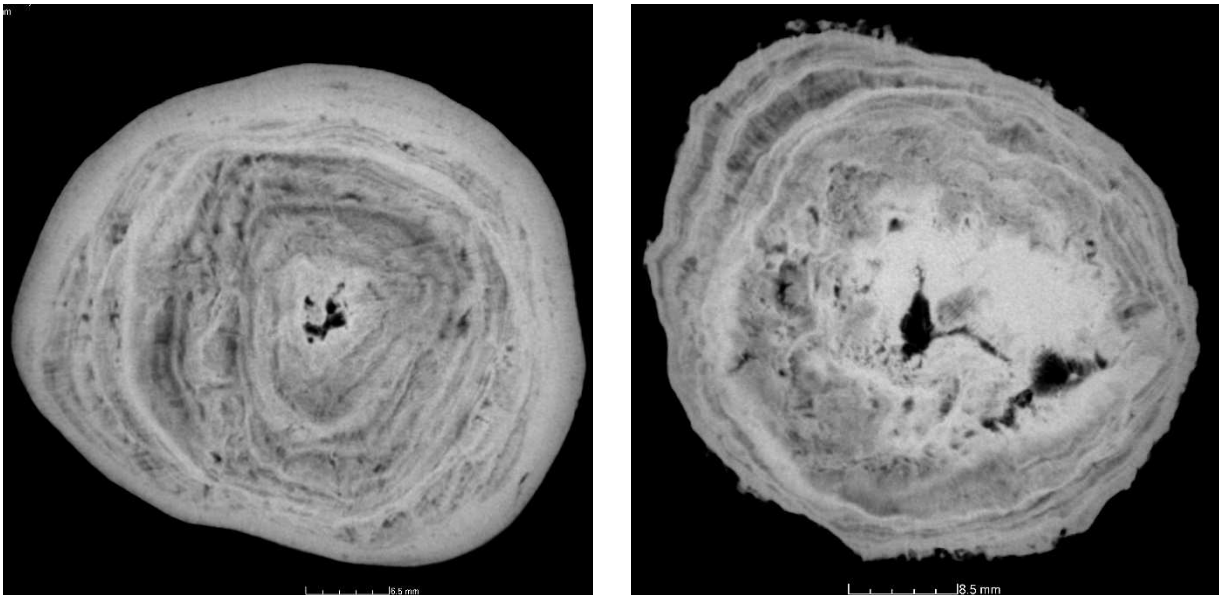
The main goal of the computer analysis of the obtained “tomographic volume” was the determination of bulk volume (Tab. 2) of irregular shaped specimens of broken speleothem (Fig. 1). Visualization and determination of the total volume of the both specimens were carried out by the VGStudio Max software (by Volume Graphics), version 2.2. The volume was calculated by software function "surface determination", which designate the threshold of the voxel CT values between air and material of dripstones body ($CaCO_3$). In the next step, the region of interest (ROI) was created by the surface of determination function. This created ROI represents a body of speleothems, and their volumes were calculated from some cubic voxels in the individual ROI and their volume (111x111x111 μm).

Figure 2 shows the 3D images of created ROI, which represent the specimens of the analysed speleothems. Figure 3 represents a typical orthogonal cross-section of speleothem highlighted on the Figure 4a and 4b by orthogonal planes (blue, red and green).



specimen no. 14483 *specimen no. 14484*

Fig. 2. 3D image of the analysed speleothem.



specimen no. 14483 *specimen no. 14484*

Fig. 3. Typical orthogonal cross-section of speleothem.

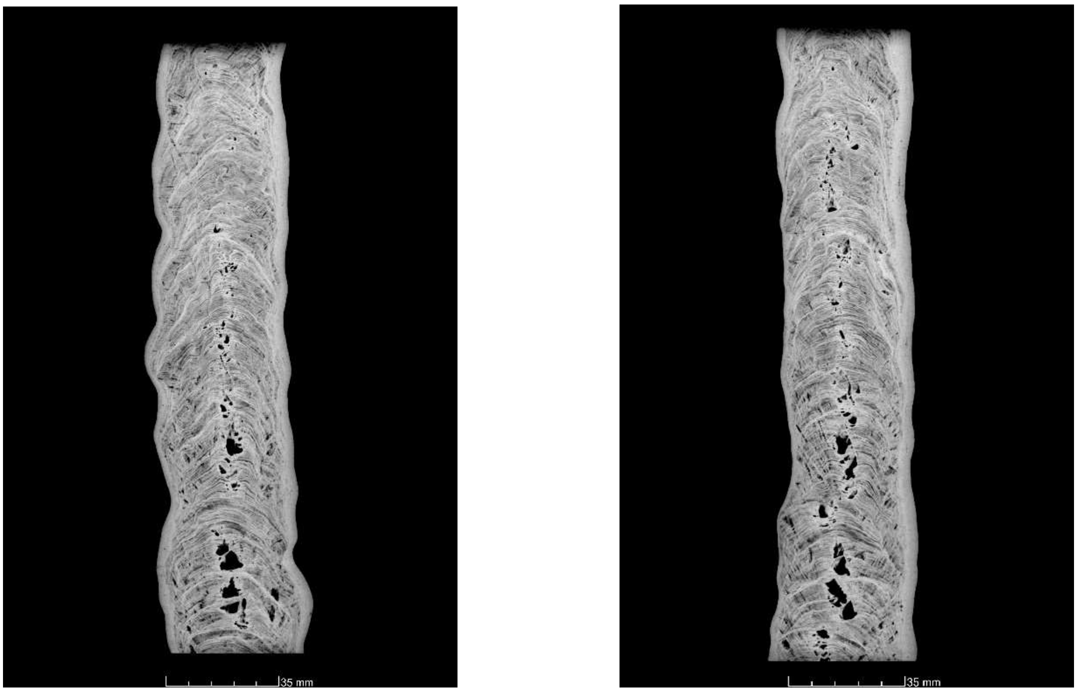


Fig. 4a Two parallel cross-sections of speleothem (specimen no. 14483).

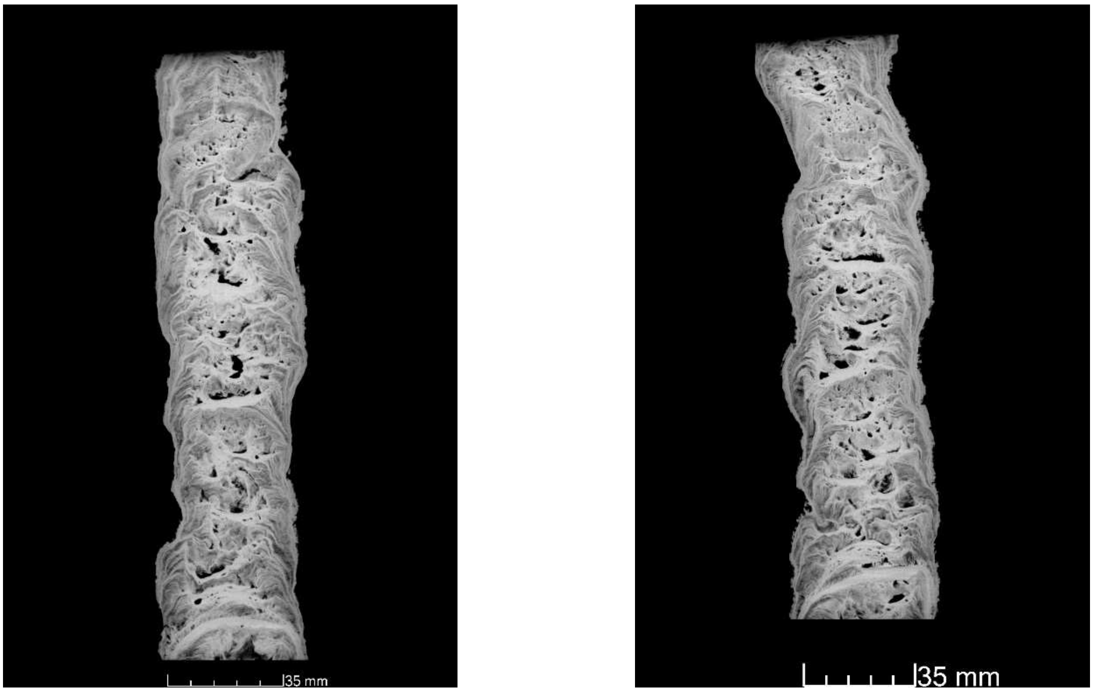


Fig. 4b Two parallel cross-sections of speleothem (specimen no. 14484).

Results

The dynamic Young´s modulus was calculated based on determined values of P-wave and S-wave velocities and bulk density determined by “Water displacement method” and by “X-Ray Computed Tomography”. The results of dynamic Young´s modulus are presented in Table 5. It is obvious that the values of the dynamic Young´s modulus are in the range 33.2 – 34.5 GPa and they are similar for both specimens and also for both used methods of bulk density determination.

Tab. 5 Calculated dynamic Young´s modulus of tested stalagmite specimens.

Specimen no.	**P-wave velocity v_p**	**S-wave velocity v_s**	**Water displacement method**	**dynamic Young´s modulus E**	**X-RAY CT method**	**dynamic Young´s modulus E**
			Bulk density ρ		**Bulk density ρ**	
	[m/s]	[m/s]	[kg/m^3]	[GPa]	[kg/m^3]	[GPa]
14483	4551	2324	2323	33.2	2334	33.4
14484	4781	2389	2235	34.0	2263	34.5

Conclusions

The presented measurements confirmed, that the dynamic Young´s modulus calculated based on values of bulk density determined by "Water displacement method" and by "X-Ray Computed Tomography" vary very little. The values of dynamic Young´s modulus calculated based on values of "X-Ray Computed Tomography" are higher than results calculated from "Water displacement method", however, the difference is less than 1.55 %. So, it could be presumed that application of „X-Ray Computed Tomography" as a tool for bulk density determination is possible.

Using this method the 3D image and information about the inner structure of tested speleothem is also obtained, and the tested specimen is not coated with wax. This means the significant advantage of "X-Ray Computed Tomography" comparing to standard "Water displacement method".

***Acknowledgement**: This article was written in connection with project Institute of clean technologies for mining and utilization of raw materials for energy use, reg. no. CZ.1.05/2.1.00/03.0082 supported by Research and Development for Innovations Operational Programme financed by Structural Founds of Europe Union and from the means of state budget of the Czech Republic, in connection with project Institute of clean technologies for mining and utilization of raw materials for energy use - Sustainability program, identification code: LO1406 supported by the National Programme for Sustainability I (2013-2020) financed by the state budget of the Czech Republic and with the long-term conceptual development support of research organisations RVO: 68145535.*

References

Aydin, A.: Upgraded ISRM Suggested Method for Determining Sound Velocity by Ultrasonic Pulse Transmission Technique. In The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014, Part I, *Springer International Publishing, 2015, pp. 95-99. DOI: 10.1007/978-3-319-07713-0_6.*

Barton, N.: Rock quality, seismic velocity, attenuation and anisotropy, *Taylor and Francis/Balkema, Leiden, Netherlands, 2007, 756 p.*

Becker, A., Davenport, CA., Eichenberger, U., Gilli, E., Jeannin, PY., Lacave, C.: Speleoseismology: A critical perspective, *J Seismol, 2006, Vol. 10, Iss. 3, pp. 371-388, ISSN 1383-4649. DOI: 10.1007/s10950-006-9017-z.*

Becker, A., Häuselmann, Ph., Eikenberg, J., Gilli, E.: Active tectonics and earthquake destructions in caves of northern and central Switzerland, *International Journal of Speleology, 2012, Vol. 41, Iss. 1, pp. 35-49, ISSN 0392-6672. DOI: 10.5038/1827-806X.41.1.5.*

Bokelmann, G., Gribovszki, K.: Constraints on long-term seismic hazard from vulnerable stalagmites. In: CSNI Workshop on "Testing PSHA results and benefit of Bayesian techniques for seismic hazard assessment", *Pavia, Italy, 2015, pp. 1-7.*

Cadorin, J.F., Jongmans, D., Plumier, A., Camelbeeck, T., Delaby, S., Quinif, Y.: Modelling of speleothems failure in the Hotton cave (Belgium). Is the failure earthquake induced?, *Netherlands Journal of Geosciences, 2001, Vol. 80, Iss. 3-4, pp. 315-321, ISSN 0016-7746.*

Forti, P.: Seismotectonic and paleoseismic studies from speleothems: the state of the art, *Geologica Belgica (vol. Karst and Tectonics), 2001, Vol. 4, Iss. 3-4, pp. 175-185, ISSN 1374-8505.*

Franklin, J.A., Vogler, U.W., Szlavin, J., Edmond, J. M, Bieniawski, Z. T.: Suggested Methods for Determining Water Content, Porosity, Density, Absorption and Related Properties and Swelling and Slake-Durability Index Properties, *Int J Rock Mech Min Sci Geomech Abstr, 1979, Vol. 16, Iss. 2, pp. 141-156, ISSN 0148-9062.*

Gribovszki, K., Bokelmann, G., Szeidovitz, Gy., Paskaleva, I., Brimich, L., Kovács, K., Mónus, P. Comprehensive investigation of intact, vulnerable stalagmites to estimate an upper limit on prehistoric horizontal ground acceleration. In C. Adam, R. Heuer, W. Lenhardt & C. Schranz (eds), Vienna Congress on Recent Advances in Earthquake Engineering and Structural Dynamics 2013 (VEESD 2013), 28-30 August 2013*, Vienna, Austria, Paper No. 445*.

Gribovszki, K., Kovács, K., Mónus P., Shen, C-C., Török, Á., Brimich, L.: Estimation the upper limit of prehistoric peak ground acceleration using the parameters of intact stalagmites and the mechanical properties of broken stalagmites in Domica cave, Slovakia, *Slovenský Kras, 2013, Vol. 51., Iss. 1., pp. 5-14, ISSN 0560-3137.*

Lacave, C., Sadier, B., Delannoy J.-J., Nehme, C., Egozcue, J.-J.: The use of speleothems to better constrain long return period seismic hazard in Lebanon. In 15th World Conference on Earthquake Engineering, Lisbonne, *Portugal, 2012, pp. 1-7.*

Lama, R.D., Vutukuri, V.S.: Handbook on Mechanical Properties of Rocks – Testing Techniques and Results, vol. II., *Trans Tech Publications, 1978, 495 p.*

Sitek, L., Bodnárová, L., Souček, K., Staš, L., Gurková, L.: Analysis of inner structure changes of concretes exposed to high temperatures using micro X-ray computed tomography, *Acta Geodyn. Geomater., 2015, Vol. 12, Iss. 1(177), pp. 79-89, ISSN 1214-9705 (Print), ISSN 2336-4351 (Online). DOI: 10.13168/AGG.2015.0009.*

Szeidovitz, G., Surányi, G., Gribovszki, K., Bus, Z., Leél-Őssy, S., Varga, Z.: Estimation of an upper limit on prehistoric peak ground acceleration using the parameters of intact speleothems in Hungarian caves, *J Seismol, 2008, Vol. 12, Iss. 1, pp. 21-33, ISSN 1383-4649. DOI: 10.1007/s10950-007-9068-9.*

Szeidovitz, G., Paskaleva, I., Gribovszki, K., Kostov, K., Surany, G., Varga, P., Nikolov, G.: Estimation of an upper limit on prehistoric peak ground acceleration using the parameters of intact speleothems in caves situated at the western part of Balkan Mountain Range, North-West Bulgaria, *Acta Geod Geophys Hu, 2008, Vol. 43, Iss. 2-3, pp. 249-266, ISSN 1217-8977. DOI: 10.1556/AGeod.43.2008.2-3.13*.

Šebela, S.: Broken speleothems as indicators of tectonic movements, *Acta Carsologica, 2008, Vol. 37, Iss. 1, pp. 51-62, ISSN 0583-6050.*