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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

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ABSTRACT:

Suitably shaped (tall, slim and more or less cylindriform), vulnerable, intact stalagmites (STM) in Domica cave have been examined. Some of these STMs are suitable to estimate the upper limit for horizontal peak ground acceleration generated by paleoearthquake. This research is the continuation of our previous examination of STMs in Baradla cave, north-east Hungary.
The density, the Young's modulus and the tensile failure stress of broken STM samples have been measured in mechanical laboratory, whereas the natural frequency and the heights and diameters of intact STMs were determined by *in situ* observation. The value of horizontal ground acceleration resulting in failure and the theoretical natural frequency of STM were assessed by theoretical calculations.
The age of the samples taken from the STM(2.26m) standing in show part of Domica cave has been determined by Multi Collector – Inductively Coupled Plasma Mass Spectrometry analysis (MC-ICPMS).
The a_g value (the upper limit for horizontal peak ground acceleration) needed to break STM(5m) in Čertova diera (Ördög-lik) hall coming from theoretical calculation is almost the same (~ 0.059 g) as - in case of STM(5.1m) in Olimposz hall (~ 0.055 g) of Baradla cave.
According to our measurements and theoretical calculations, in the last 2-5 kyears the geological structures close to Baradla and Domica caves have not generated paleoearthquakes, which would have produced horizontal ground acceleration larger than 0.061g. This value can be reached even in moderate size earthquakes. Our result has to be taken into account when calculating the seismic potential of faults near to Domica cave (e.g. Darnó, Plešivec (Pelsőc) and Rožňava (Rozsnyó) lines)

Introduction

It is very important to obtain an unbiased estimate of seismic hazard, because it is one of the most important factors controlling the costs of building construction. The seismic hazard of an area of interest is specified in terms of the horizontal ground acceleration which shall not be exceeded with a given probability within a certain time period. Estimating seismic hazard appropriately requires above all the information on the largest earthquake that has occurred in the past.

The most of the large earthquakes occur at plate boundaries. However in territories with low or moderate seismic activity, as intraplate areas, the recurrence time of large earthquakes, belonging to the same source zone, can be as long as 10 000 years (Scholz [1990]). Therefore in territories with low or moderate seismic activity such information is usually not available since earthquake catalogues do not contain sufficiently long time period, as they are based characteristically on 1000 to 2000 years observational period. The lack of knowledge about these largest earthquakes is therefore usually balanced by assumptions about earthquake statistics and/or fault geometry. Those assumptions are difficult to quantify, rendering hazard estimation arbitrary and thus questionable.

To obtain more reliable and realistic data regarding the frequency and magnitude of earthquakes, we can investigate paleoearthquakes, which occurred before historic times. The research of the relationship between earthquakes and the growth, tilting and breaking of speleothems is promising, and investigations of this kind have been initiated in recent times (Forti and Postpischl [1984, 1988]; Delaby [2001]; Cadorin et al. [2001]; Lacave et al. [2000, 2004]; Kagan et al. [2005], Becker et al. [2006]).

The relationship between earthquakes and the growth and breaking of intact and vulnerable stalagmites have already been investigated earlier in Hungary (Szeidovitz et al. [2008, 2007, 2005]), and after that in Bulgaria (Paskaleva et al. [2008, 2006], Szeidovitz et al. [2008a], Gribovszki et al. [2008]).

Slovakia is rather rich in dripstone caves, however similar investigations of intact and slim stalagmites for the aim of seismic hazard did not complete before our research. Recently, research cooperation between us and Austrian and Czech colleagues in similar stalagmite investigation began.

Vulnerable stalagmites can be found in Baradla cave, Hungary, and in its continuation, Domica cave, Slovakia. These vulnerable stalagmites are well suited to the paleoseismic investigations; that is, they have the necessary large height/diameter ratio. Our investigations suggest that these stalagmites can be broken even at low horizontal acceleration (<0.6 m/s^2). These speleothems therefore can be used as indicators, whether or not large paleoearthquakes occurred in the surroundings of the investigated caves.

The acceleration level (determined by our previous stalagmite investigation) for the territory of Baradla cave is lower than the PGA value determined by probabilistic seismic hazard calculation (Tóth et al. [2006]) for a much shorter period of time, and evidently, the expected PGA would be even greater for a 70 000-year interval.

Aim and method of our research

The aim of our research is: estimating the upper limit for horizontal peak ground acceleration generated by paleoearthquake. Specially shaped, (more or less cylindriform), intact, slim and vulnerable stalagmites were chosen for the estimation.

The steps of our investigation are the following:

- non-destructive determination of the natural frequencies and the dimensions of slim intact/unbroken stalagmites *in situ*;
- laboratory measurements of the mechanical properties of broken stalagmites:
    - density,

- o velocity of elastic waves propagating in stalagmite samples;
- o tensile failure stress;

— theoretical calculations of the static horizontal ground acceleration value (a_g), which would break the intact stalagmites;

— extraction of core samples of STM(2.26m) stalagmite standing in the show part of Domica cave from its top and bottom, in order to determine its age and rate of growing;

Earthquake activity of the Pannonian region

Generally it can be stated that the seismicity in the Pannonian region is moderate and low compared to the peripheral areas as the Dinarides or the Vrancea area, where the seismicity is much higher. The distribution of earthquakes is diffuse, which means it is difficult to find connections between the hypocenters and the tectonic faults.

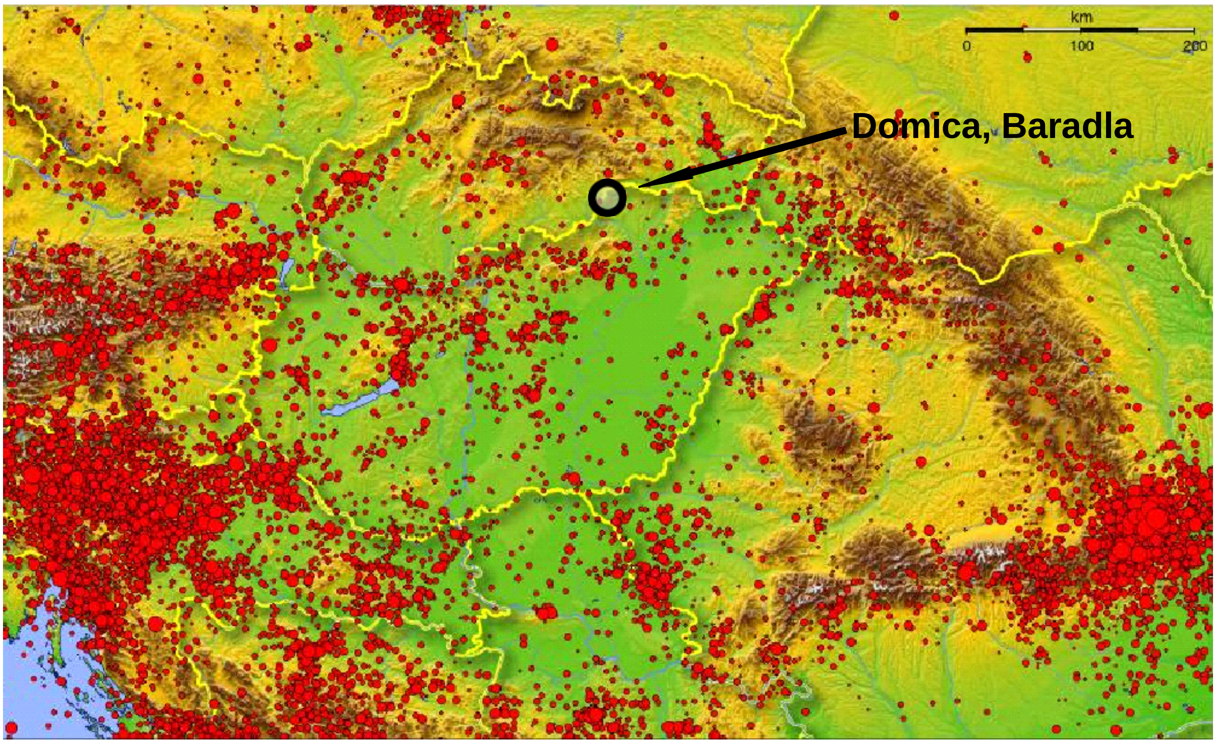


Figure 1. Seismicity of the Pannonian region and location of Baradla-Domica cave system (Tóth & Mónus)

The Pannonian region is situated between the Mediterranean area, which is one of the seismically most active regions in the world, and the East European platform, which can be treated as nearly aseismic.

Baradla-Domica cave system and the investigated stalagmites

Baradla-Domica cave system is located in the Gemer – Turňa (Gömör-Torna) karst region, Northern Hungary and Southern Slovakia, exactly at the border of these two countries.

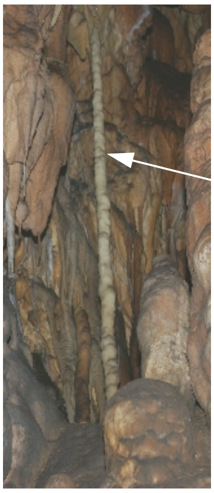
The Hungarian part of this cave system was investigated a few years ago (Szeidovitz et al. [2008, 2007, 2005]) by using the same method as in this paper on Domica cave. As the conclusion of our investigation in Baradla cave we can state that few stalagmites with large height/diameter ratio (H/D>40) have been found. In case of the 5.1 m high stalagmite in Olimposz hall of Baradla cave, the computed a_g value was especially low and attainable even in the case of moderate sized earthquakes. On the basis of our measurements and theoretical calculations, we can assume that the geological structures close to the Baradla cave (Fig. 1) did not generate paleoearthquakes producing a horizontal ground acceleration larger than 0.05 g in the last 70 kyears.

Since our investigation was successful at the Hungarian part of Baradla-Domica cave system, that motivated us to investigate Slovak part of this cave system (Domica).

It is known that seismic waves in caves attenuate with depth (Becker et al. 2006). Therefore, it is important to mention that the investigated stalagmites are situated at shallow depths. Near to lake in the show part of Domica cave the investigated STM(1.8m) is located at about 80 m below surface. The Čertova diera (Ördög-lik) hall can be found 20-30 m beneath the surface.

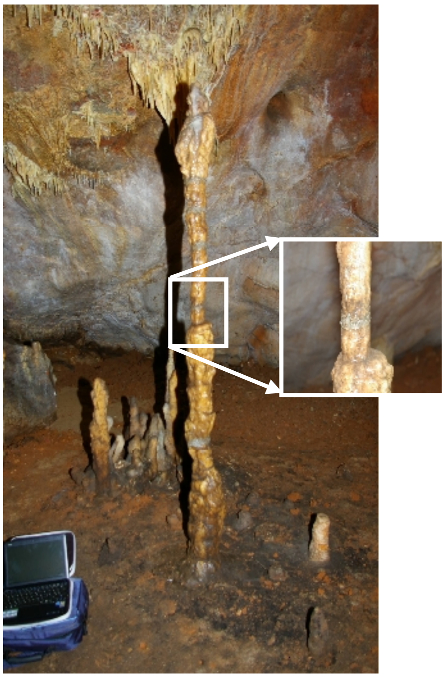
From our experience we can state that stalagmites with H/D (height/diameter) ratio higher than 20 can be used for our investigation. In this case the eigenfrequency of stalagmite is low enough to fall into the frequency range of nearby earthquakes (which is less than 20 Hz) (Lacave et al. [2000]). If the natural frequency of the stalagmite is in the frequency range of nearby earthquakes then the failure acceleration can be much smaller than our calculated a_g value because of the resonance effect.

We have found and investigated several different slim stalagmites in the show part, and in Čertova diera (Ördög-lik) hall of Domica cave (Fig. 2). Almost all of the slim stalagmites are broken and stuck together at the show cave part of Domica (Fig. 2, STM(1.84m) broken). We can conclude that these broken and stuck together stalagmites could have been destroyed nowadays, maybe by human impact.



STM(1.8m)

STM(2.26m)
in show part of Domica cave, the core samples for age determination were extracted from this stalagmite. Behind and above the STM(2.26m), STM(1.8m) can be seen.



STM(1.84m)
broken and stuck together

Figure 2. Some of our investigated stalagmites at the show part of Domica cave

We could find and measure only one intact and slim STM(1.8m) situated at the end of Panenská chodba (Szűzfolyosó) next to Lake of Domica in the show cave part, since all the other slim and vulnerable stalagmites were broken and stuck together. We recorded the oscillation of this STM(1.8m), measured the dimensions of it and took core-samples for age determination from STM(2.26m), beneath the STM(1.8m) (Fig. 2, middle photo). We used STM(2.26m) for age determination, because taking core samples from STM(1.8m) is impossible without destroying it.

The intact STM(5m), we found in Čertova diera (Ördög-lik) hall, has the most suitable shape we have ever found (Fig. 3). The height of this STM(5m) is about 5 m, and the average diameter of this cylindriform stalagmite is less than about 6cm. There is no entrance to the Čertova diera (Ördög-lik) hall from the show cave part of Domica till now, and special caver equipment is needed to climb down to this hall.

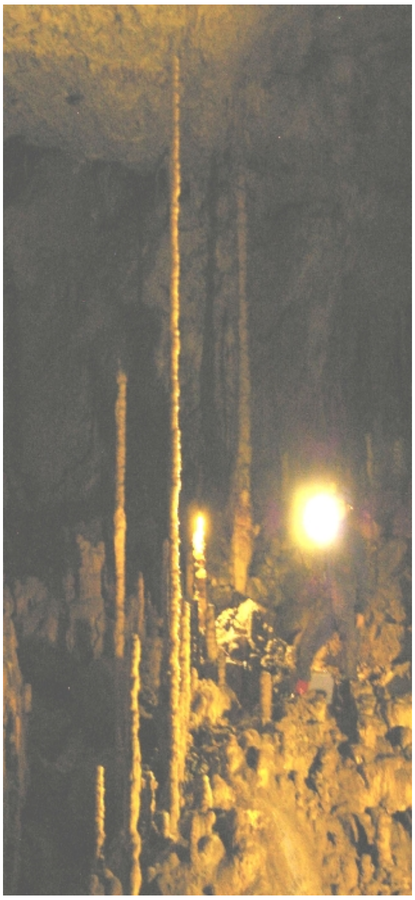


Figure 3. Tall and slim stalagmite STM(5m) in Čertova diera (Ördög-lik) hall

Non-destructive *in situ* measurements in caves

Considering that *in situ* measurements of these slim and tall stalagmites (STM) had to be done non-destructively (because all speleothems in Slovakia are under nature protection), we confined ourselves only to determine their dimensions and natural frequencies.

In order to measure the natural frequency, geophones were fastened on the stalagmites by adhesive tape, and they were excited by small amplitude forced vibrations induced by a gentle hit. It can be seen in Table 1, that all the measured lowest natural frequencies (f_0) of STMs are below 20 Hz, this means that they fall into the frequency range of nearby earthquakes.

If the natural frequency of stalagmite is below 20 Hz then resonance can occur during a local earthquake. Our theoretical calculations based on cantilever beam theory did not take into consideration the phenomenon of resonance, which means that in reality the STMs would break at lower values of horizontal acceleration than the computed ones.

The horizontal acceleration of a stalagmite was registered by an SM6 geophone (its natural frequency is 10 Hz) and sampled by a SIG SMACH SM-2 digitiser. The results of non-destructive *in-situ* examinations of stalagmites can be seen in Table 1. In the f_1 column „geophone" means, that this eigenfrequency could be an artefact due to the proximity to the eigenfrequency of SM6 geophone.

Figure 4. shows the oscillation and its power spectral density of STM(1.8m) along the recorded signal of the excited stalagmite.

Figure 5. shows power spectral density of oscillation of STM(5m).

Table 1. Results of non-destructive in-situ examinations of stalagmites: dimensions and measured natural frequencies

ID	**LOCATION**	**HEIGHT (m)**	**DIAMETER (cm)**	**H/D**	**measured f_0 (Hz)**	**measured f_1 (Hz)**	**measured f_2 (Hz)**
STM(5m)	Domica cave, Čertova diera hall	5.00	average: 5 (7-4)	100	2	10.2; 10.6 geophone	26; 27
STM(1.8m)	Domica cave, Panenská chodba	1.80	average: 5 (6-4)	36	6-8	12.7; 13.3 geophone	
STM(2.26m)	Domica cave, Panenská chodba	2.26	average: 8 (11-4)	28	14.2		
STM(2.39m)	Domica cave, next to entrance	2.39	irregular shape	--	7.3; 8.1	30.6	

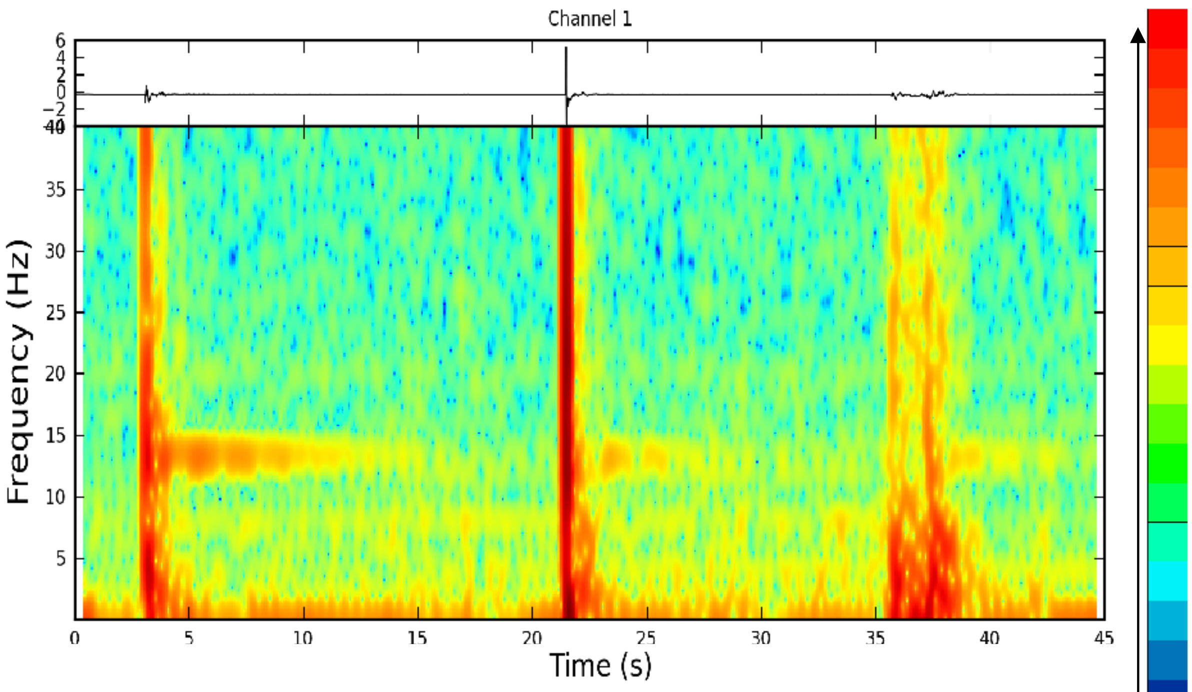


Figure 4. The oscillation and its power spectral density of STM(1.8m) along the recorded signal of the excited stalagmite

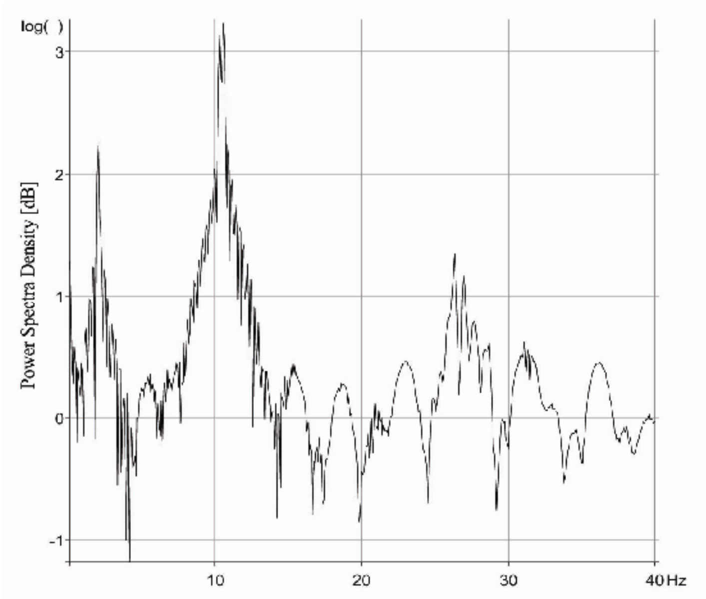


Figure 5. Power spectral density of oscillation of STM(5m)

Power spectral density of oscillation show that the eigenfrequency of stalagmite STM(5m) is around 2 Hz, that is within the frequency range of near earthquakes. The eigenfrequency values of stalagmite STM(1.8m) and STM(2.26m) are also below 20Hz. It means that the phenomenon of resonance would come into play on these stalagmites in the case of an earthquake occurring near the investigated cave.

Oscillation of stalagmites by theoretical calculations and results of mechanical laboratory tests

In case of ideally shaped stalagmites (cylindrical with constant diameter) the following simple equations based on cantilever beam theory can be used for the calculation of the eigenfrequency and the horizontal ground acceleration resulting in failure of a stalagmite (Cadorin et al. [2001], Lacave et al. [2000]).

The natural frequency of a stalagmite:

$$f_0 \approx \frac{1}{\pi}\sqrt{\frac{3.1ED^2}{16\rho H^4}} \tag{1}$$

The horizontal ground acceleration resulting in failure of a stalagmite:

$$a_g = \frac{D\sigma_u}{4\rho H^2} \tag{2}$$

where *D:* diameter; *H*: height of stalagmite; ρ: mass density of stalagmite; *E*: dynamic Young’s modulus; σ_u: tensile failure stress

Values of density, Young’s modulus and tensile failure stress have been based on mechanical laboratory measurements (Brazilian test, ultrasonic velocity measurement). Measurements have been carried out in mechanical laboratory of the Budapest University of Technology and Economics, Department of Construction Materials and Engineering Geology. Results are summarized in Table 2.

Table 2 Results of mechanical laboratory tests

	density, ρ [kg/m^3]	dynamic Young'smodulus, E [GPa]	tensile failure stress, σ_u [MPa]
show part of Domica cave (7 samples)	2368.1± 104.1	23.1±4.4	2.52±0.36
Čertova diera hall of Domica cave (6 samples)	2347.6 ±115.8	23.6±4.0	2.75 ±0.56

Our results show that the failure tensile stress values of broken dripstone samples from Čertova diera (Ördög-lik) hall (σ_u=2.75 MPa) are higher than the values of Baradla cave Olimposz hall samples, though dynamic Young's modulus values are almost the same (E=23.6 GPa and E=20.8 GPa respectively).

Table 3 is the same as Table 1 but completed with eigenfrequency (f_0) and horizontal ground acceleration resulting in failure (a_g) values. These values are the results of laboratory tests and theoretical calculations based on stalagmite dimensions.

Table 3. Table 1. completed with natural frequency and horizontal ground acceleration resulting in failure obtained by theoretical calculations

NAME	LOCATION	HEIGHT (m)	DIAMETER (cm)	H/D	measured f_0 (Hz)	theoretical f_0 (Hz)	a_g (m/s2)
STM(5m)	Domica cave, Čertova diera hall,	5.00	average: 5 (7-3.5)	100	2	0.9	0.59
STM(1.8m)	Domica cave, Panenská chodba	1.80	average: 5 (6-4)	36	6-8	6.6	4.11
STM(2.26m)	Domica cave, Panenská chodba	2.26	average: 8 (11-4)	28	14.2	6.7	4.17
STM(2.39m)	Domica cave, next to entrance	2.39	irregular shape	--	7.3; 8.1	---	---

The formulae (1, 2) could not be applied in the case of stalagmite STM(2.39m) because of its irregular inversely flared shape, far from cylindric.

The calculated eigenfrequency values are lower than the measured ones. Differences might be the consequences of approximations, neglections and generalizations applied. For example the real shape of stalagmites was not regularly cylindric or the dripstone material is not homogeneous and the physical parameters used during calculations had been derived from mechanical tests of different stalagmite samples.

Horizontal ground acceleration resulting in failure are between 0.59 and 4.17 m/s^2 in static case. These calculations do not take into account the phenomenon of resonance that can arise in stalagmites with low natural frequencies during a local earthquake .

Age determination

Samples have been taken from the STM(2.26m) stalagmite with the help of core drilling at the base and 5cm below the tip. The diameter of the drill cores was 12mm.

Age determination has been carried out according to the MC-ICPMS method at the „High-precision Mass Spectrometry and Environment Change Laboratory (HISPEC)" in Taiwan.

These datings show that the stalagmite base is 116 thousand years old and the upper sample is recent. According to these results the average growth rate of this dripstone is around 2 mm/100 years. Comparing this value to the average growth rate of the 5.1m high Baradla stalagmite mentioned earlier (Szeidovitz et al. [2008a]), we can conclude that the particular Baradla stalagmite had been growing cca. 3 times faster, than the one from Domica.

Based on these growth rates we can timidly suggest that the stalagmite standing in the Čertova diera (Ördög-lik) hall of Domica cave (now 5 m high) could have a height of 4.9 m 2-5 thousand years ago.

Summary

Based on laboratory measurements and calculations we can state that the horizontal ground acceleration resulting in failure of the 5 m high stalagmite standing in Domica cave Čertova diera (Ördög-lik) hall is a_g=0.059 g.

The 2.26 m high Domica cave stalagmite is, according to the age determination of its samples, still growing. The base of this stalagmite is not older than 116 000 years. Taking into account that the extrapolation of these measurements to another stalagmite is very questionable, we can just very timidly suggest that the height of the Čertova diera (Ördög-lik) hall stalagmite (with recent height of 5 m) could be 4.9 m 2000-5000 years ago. Assuming this 4.9 m height in our calculations, this stalagmite should have been broken as a result of a ground movement with an acceleration of about 0.061 g. Consequently, in the near vicinity of the Baradla-Domica cave system, including the Slovak side, there could not have occurred earthquakes with horizontal ground accelerations greater than 0.061 g in the past few thousand years. This ground acceleration value is still slightly lower and valid for a much longer time period than the 0.068 g result of an earlier PSHA study (Tóth et al. [2006]) for the Baradla-cave region (10% probability of exceedance in 50 years).

This ground acceleration level can be caused even by a moderate earthquake.

According to the results of non-destructive tests carried out in the cave, the eigenfrequency of the 5 m high stalagmite of Čertova diera (Ördög-lik) hall is around 1-2 Hz. This low natural frequency can lead to resonance in the case of a local earthquake which can cause failure of the stalagmite even at lower levels of accelerations i.e. horizontal ground acceleration levels below 0.059 g.

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