Estimation of an upper limit on prehistoric peak ground acceleration using the parameters of intact stalagmites and the mechanical properties of broken stalagmites in Domica cave, Slovakia

K. GRIBOVSZKI (1), K. KOVÁCS (1), P. MÓNUS (1), CHUAN-CHOU SHEN (2), Á. TÖRÖK (3), L. BRIMICH (4)

(1) Geodetic and Geophysical Institute, Research Centre for Astronomy and Earth Science, Hungarian Academy of Sciences, kgribovs@ggki.hu
(2) Department of Geosciences, National Taiwan University
(3) Engineering Geology Division, Department of Construction Materials and Engineering Geology, Budapest University of Technology and Economics
(4) Geophysical Institute, Slovak Academy of Sciences

ABSTRACT:

Special shaped (high, 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 method of our investigation is the same as before: 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 height 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 a STM(2.26m) standing in show-cave part of Domica cave have been determined by Multi Collector – Inductively Coupled Plasma Mass Spectrometry analysis (MC-ICPMS).
The a_g value (upper limit for horizontal peak ground acceleration needs to break STM(5m) in Ördög-lik Hall) coming from theoretical calculation is almost the same (~ 0.059g) as it is in case of STM(5.1m) in Olimposz Hall (~ 0.055g).
On the grounds of our measurements and theoretical calculations, we can state that the geological structures close to Baradla and Domica caves did not excite such paleoearthquakes in the last 2-5 kyears, which would have produced horizontal ground acceleration larger than 0.061g. This value can arise even in case of 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-, Pelsőc- and Rozsnyó lines)

Introduction

Why is it important to estimate the upper limit of horizontal ground acceleration for a given area and for a few 10 kyears in the past?

It is very important to obtain an unbiased view of seismic hazard, which is one of the most important factors controlling costs of building construction. Estimating seismic hazard appropriately requires above all, information on the largest earthquake that can occur.

The most of the large earthquakes occurred 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 enough long time period, as they are based characteristically on 1000 to 2000 years observational period. Knowledge about these largest earthquakes is therefore usually replaced 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 the continuation of it, at the 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 at the surrounding 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. For the estimation special shaped, (more or less cylindriform), intact, slim and vulnerable stalagmites were chosen.

The steps of our investigation are the following:

- determining non-destructively the natural frequencies and the dimensions of slim intact/unbroken stalagmites in situ in the cave;
- measuring in laboratory the mechanical properties of broken stalagmites:
    - density,
    - velocity of elastic waves propagated in stalagmite samples;
    - tensile failure stress;
- assessing by theoretical calculations the static horizontal ground acceleration value (a_g), which would break the intact/unbroken stalagmites;
- taking core samples from STM(2.26m) stalagmite standing in show cave part of Domica cave at two level: top and bottom, in order to determine its age and rate of growing;

The consequences coming from the results are: since the investigated stalagmites still stand and intact, therefore we can state, that a paleoearthquake producing such high horizontal ground acceleration value could not have generated since the time the stalagmites stand in the same shape.

Earthquake activity of the Pannonian region

Generally it can state that the seismicity in 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.

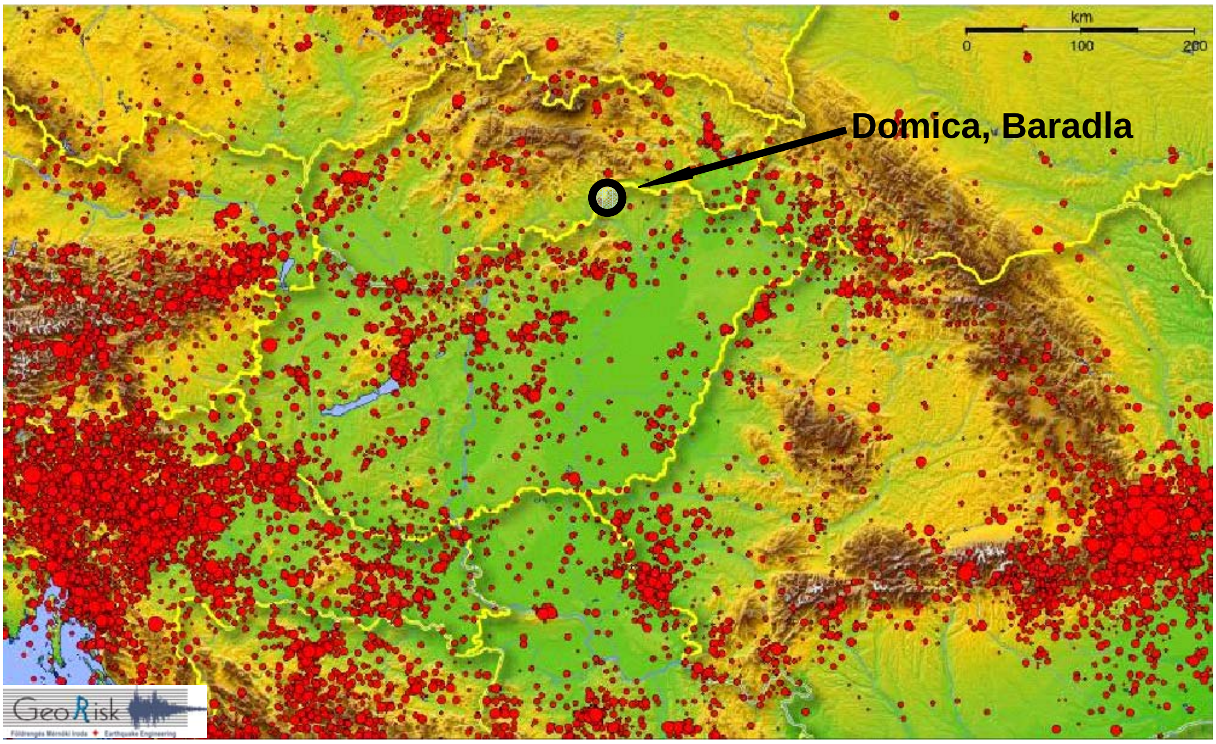


Figure 1. Seismicity of the Pannonian region and location of Baradla-Domica cave system

The Pannonian region is situated between the Mediterranean area, which is one of the most seismically 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 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 in Domica cave. As the conclusion of our investigation in Baradla cave it can state that few stalagmites with large height/diameter ratio (H/D>40) have been found. The computed a_g values for the studied stalagmites was especially low in case of the 5.1 m high stalagmite in Olimposz hall of Baradla cave, which can arise 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 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 gave us the idea to investigate Slovak part of this cave system (Domica) would be useful.

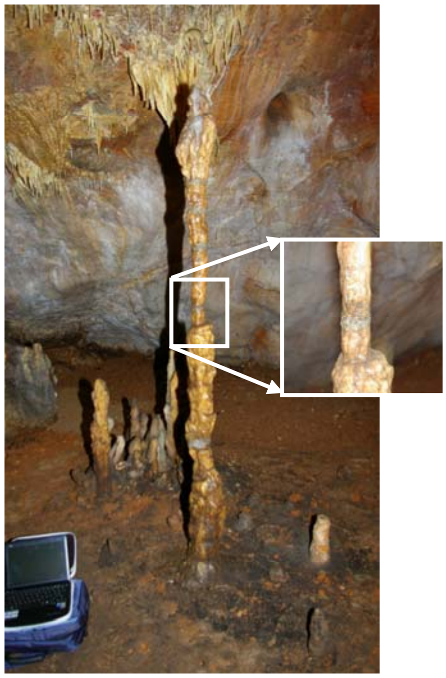
Since it is known that, with the deepening of the caves, the attenuation of the seismic waves rises (Becker et al. 2006), therefore, it is important to mention that the caves where the investigated stalagmites stand are situated at shallow depth. Near to lake of the show cave part of Domica cave the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

As a practical experiences we can state that stalagmites with H/D (height/diameter) ratio higher than 20 can be used for our investigation. Since in this case the eigenfrequency of stalagmite is enough low, and fall in 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 even smaller than our calculated a_g value (by cantilever beam theory) because of the resonance effect.

We have found and investigated several different slim stalagmites at the show cave part, and in 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 concluded, that these broken and stuck together stalagmites could be destroyed nowadays, and maybe by human impact.

STM(1.8m)

STM(2,26m)
in show cave part of Domica cave,
the core-samples for age
determination were taken from this
stalagmite.
Behind and over to 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 cave part of Domica cave

We could find and measure only one intact and slim STM(1.8m) situated at the end of Szűzfolyosó (Panenská chodba) next to Lake of Domica at 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), below and next to 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.)

In Ördög-lik Hall we have found such a suitable, intact STM(5m), as such as suitable we have never been found before (Fig. 3). The height of this STM(5m) is about 5m, and the average diameter is less than about 6cm of this cylindriform stalagmite. (There is no entrance to the Ördög-lik hall from the show cave part of Domica till now, and special caver equipments need to climb down to this hall.)

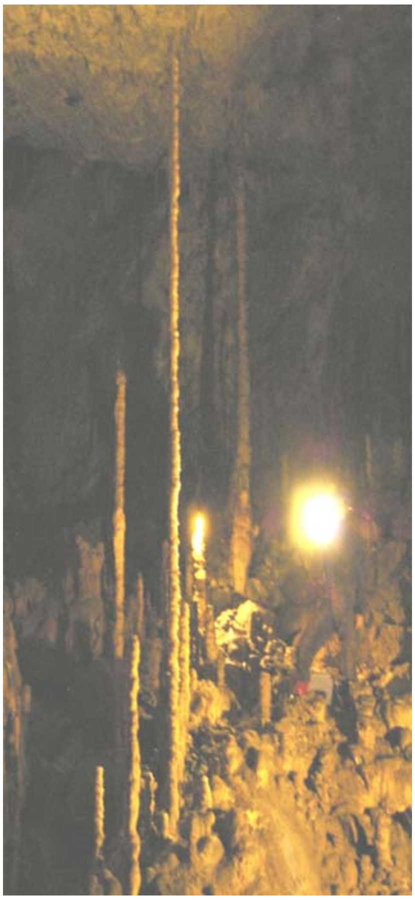


Figure 3. Tall and slim stalagmite, STM(5m) in Ördög-lik hall

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 of the stalagmites in Slovakia are under nature protection), we confined ourselves only to determine the dimensions and natural frequencies of them.

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

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

The horizontal acceleration of a stalagmite was registered by an SM6 geophone (its natural frequency is 10Hz) and the data logger was a SIG SMACH SM-2 digitiser. The results of non-destructive in-situ examinations of stalagmites can be seen at Table 1. At the f_1 column „geophone" means, that maybe this eigenfrequency can be caused by the self frequency of SM6 geophone.

Figure 4. shows the oscillation and 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, Ördög-lik Hall	5.00	average: 5 (7-4)	100	2	10.2; 10.6 geophone	26; 27
STM(1.8m)	Domica cave, Szűzfolyosó	1.80	average: 5 (6-4)	36	6-8	12.7; 13.3 geophone	
STM(2.26m)	Domica cave, Szűzfolyosó	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	

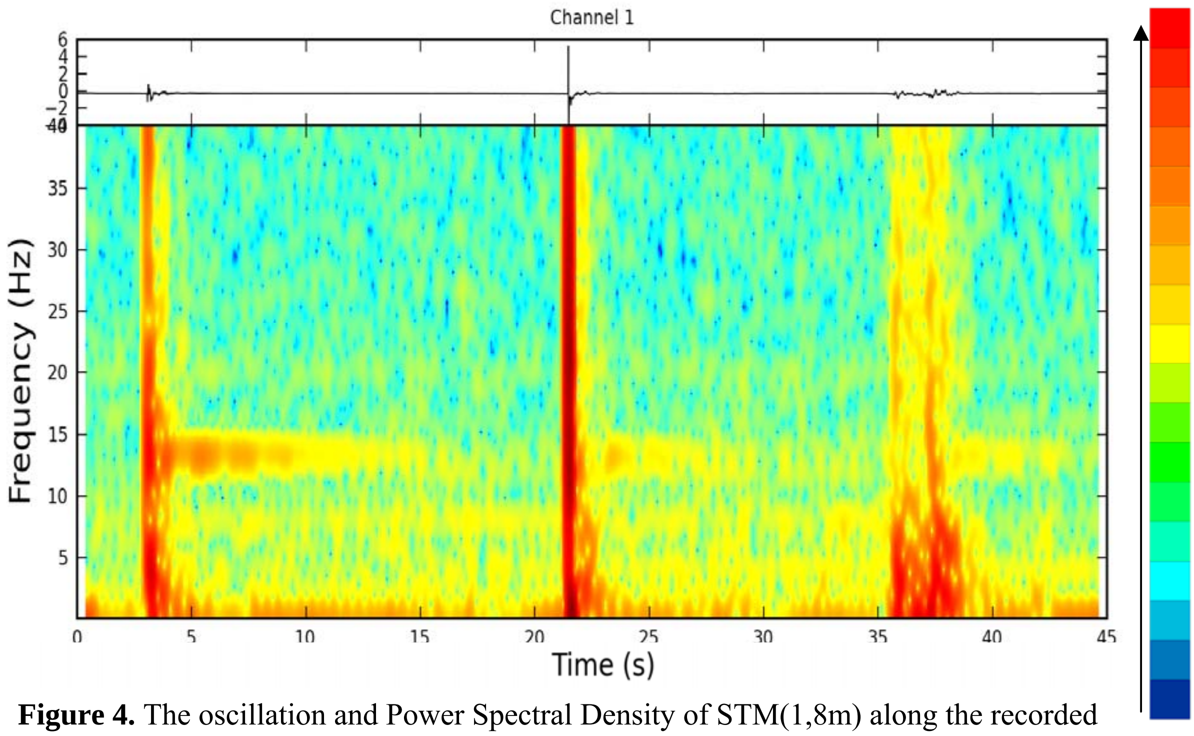


Figure 4. The oscillation and Power Spectral Density of STM(1,8m) along the recorded signal of the excited stalagmite

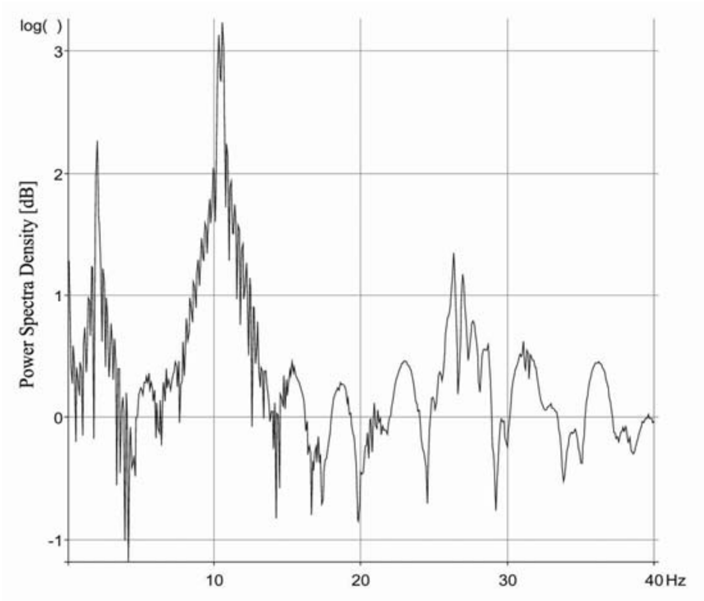


Figure 5. Power Spectral Density of oscillation of STM(5m)

Power Spectral Density of oscillation show that the eigenfrequency of stalagmite STM(5m) is around 2Hz, 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 occur near the investigated cave.

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

In case of ideal shaped stalagmites (cylindrical with constant diameter) the following simple equations 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] by cantilever beam theory.

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: density of stalagmite; *E*: dynamic Young's modulus; σ_u: tensile failure stress

Values of densities, 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 (mean values)

	density, ρ [kg/m^3]	dynamic Young-modulus, E [GPa]	tensile failure stress, σ_u [MPa]
show cave part of Domica cave (7 samples)	2368.1± 104.1	23.1±4.4	2.52±0.36
Ördög-lik 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 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*) 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, Ördög-lik hall,	5.00	average: 5 (7-3.5)	100	2	0.9	0.59
STM(1.8m)	Domica cave, Szűzfolyosó	1.80	average: 5 (6-4)	36	6-8	6.6	4.11
STM(2.26m)	Domica cave, Szűzfolyosó	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 normal formulae for calculations could not be applied in the case of stalagmite STM(2.39m) because of its irregular inversely flared shape, far from cylindric.

Regarding eigenfrequencies calculated 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 59 and 417cm/s^2 in static case. These kinds of calculations do not take into account the phenomenon of resonance that can arise as a result of an earthquake in the case of stalagmites with low natural frequencies.

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 growing velocity of this dripstone is around 2 mm/100 years. Comparing this value to the average growing velocity of the 5.1m high Baradla stalagmite mentioned earlier [Szeidovitz et al. 2008a], we can conclude that the Baradla dripstone had been growing cca. 3 times faster, than the Domica one.

Based on these growing speed values we can say that the stalagmite standing in the Ördög-lik hall of Domica cave (now 5m high) could have a height of 4.9m 2-5 thousand years ago.

Summary

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

According to the age determination of samples from the 2.26m high Domica cave stalagmite this dripstone is still growing. Even the base of this stalagmite is not older than 116 000 years. Based on these measurements and also on calculations we can say that the height of this Ördög-lik hall stalagmite (with recent height of 5m) could be 4.9m 2000-5000 years ago. Assuming this 4.9m height, this stalagmite should have been broken as a result of a ground movement with an acceleration of about 0.061g, according to our calculations. Consequently, there could not have occurred earthquakes in the near vicinity of the Baradla-Domica cave system, including the Slovakian side, that could cause horizontal ground accelerations greater than 0.061g in the past few thousand years. This ground acceleration value is still slightly lower and valid for a much longer time period than the 0.068g 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 5m high stalagmite of Ördög-lik hall is around 1-2 Hz. This low level of 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 0.059g.

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