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Comprehensive investigation of intact, vulnerable stalagmites to estimate an upper limit on prehistoric horizontal ground acceleration

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Abstract. Non-intrusive in situ measurements were carried out in caves in Hungary, Bulgaria and Slovakia in order to determine the fundamental frequencies (FF) and horizontal ground accelerations (HGA) resulting in failure of intact, slim, vulnerable stalagmites. Similar investigations are planned in Austria at the Eastern Alps. The main steps of investigation are: 1) FF of intact stalagmites were determined by in situ observation. 2) Density, Young's modulus and tensile failure stress of broken stalagmites have been measured in mechanical laboratory. 3) The value of HGA resulting in failure and FF of stalagmite were assessed by theoretical calculations. 4) Age determination of core-samples. The upper limit for HGA, a_g, for slim stalagmites determined by theoretical calculations, can arise even for moderate-sized earthquakes. The FF of the investigated stalagmites are low. The geological structures close to the investigated caves did not excite paleoearthquakes in the determined time period, corresponding to HGA larger than the determined a_g values.

Keywords: Stalagmite; Natural frequency; Seismic hazard; Prehistoric earthquake

1 INTRODUCTION

In territories with low or moderate seismic activity, the recurrence time of large earthquakes belonging to the same source zone can be as long as 10 kyr (Scholz 1990) (1kyr = 1000 years). Therefore, we cannot draw well-grounded inferences in the field of seismic hazard assessment using exclusively the data of earthquake catalogues, as they are based characteristically on 1- to 2-kyr observational period. To obtain more reliable and realistic data regarding the frequency and magnitude of earthquakes, we have to investigate paleoearthquakes that occurred before historic times. Neotectonic and geomorphologic investigations can reveal the traces of paleoearthquakes only in some lucky circumstances, as erosion can easily destroy the superficial formations. 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. A short summary about this topic can be found in Szeidovitz (2008a).

The authors of this paper were the first ones to carry out non intrusive in situ measurements in Hungarian, Slovak and Bulgarian caves in order to determine the fundamental frequencies (FF) and horizontal ground acceleration (HGA) resulting in failure of intact, slim stalagmites. The territory of Hungary, Slovakia and Bulgaria is rather rich in dripstone caves. Discussions with experts and our visits to caves, it seems that, in Hungary, only in the Hajnóczy and Baradla caves (Figure 1) can be found speleothems that are well suited to paleoseismic investigations; that is, they have the necessary large height/diameter ratio (Cadorin et al. 2001). Our preliminary investigations suggested that the stalagmites of these caves can break even at low HGA. These speleothems therefore could be used as indicators whether or not large paleoearthquakes occurred within the given region.

Baradla cave is located in Northern Hungary, in Gömör-Torna karst region at the Slovak and Hungarian border (Figure 1). Baradla cave has a part at Slovakia as well, named Domica. We have also investigated stalagmites in Domica cave and have found a very vulnerable one at Ördög-lik Hall.

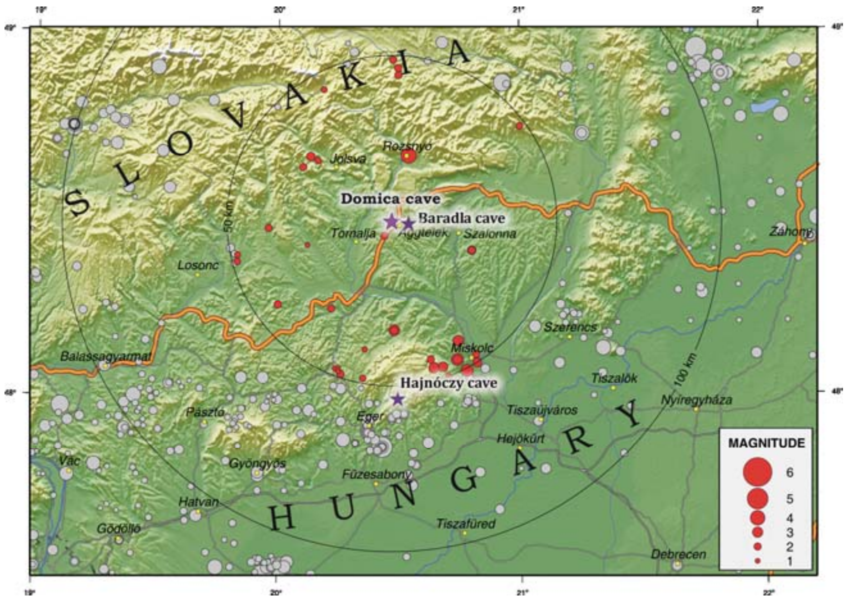

Figure 1. Location of Baradla, Domica and Hajnóczy caves in Northern Hungary and the historical and instrumental seismicity of this region.

Vulnerable stalagmites have been investigated in four different caves in Bulgaria: Varteshkata, Elata, Snezanka and Eminova. Varteshkata and Elata caves are situated in the north-western part of Bulgaria (Figure 2), including the western ridge of Balkan Mountain Range, so called Vratsa Balkan region. Snezanka and Eminova caves are situated in the South Western part of Bulgaria (Figure 2), including part ridge of Rhodope Mountain, known as one of the richest cave regions in the country. The names of the caves involved in our investigations in different countries and the number of measured stalagmites in caves can be seen in Table 1. In this paper we present only our results connection with the most vulnerable stalagmite in each cave.

Table 1. The names of the caves involved in our investigations in different countries and the number of measured stalagmites in each cave

Name of cave	Country	Number of stalagmites at the given cave
Baradla	Hungary	6
Hajnóczy		1
Domica	Slovakia	4
Varteshkata	Bulgaria	2
Elata		1
Snezanka		2
Eminova		1

2 SEISMICITY OF THE SURROUNDINGS OF THE INVESTIGATED CAVES IN HUNGARY, SLOVAKIA AND BULGARIA

The seismic activity inside the Pannonian basin can be considered moderate compared to that of the peripheral areas (Tóth et al. 2002). The number of earthquakes is the relatively small and the distribution of epicentres is diffuse. The earthquake activity and present-day deformation are mainly driven by the counterclockwise rotation and northwards indentation of the Adriatic microplate (Bada et al. 1999). According to the Hungarian Earthquake Catalogue (Zsíros 2000), which contains earthquakes as from the year 456 a.d., the maximum observed magnitude was 6.3 in the Hungarian part of the Pannonian basin. In spite of the diffuse characteristics of the earthquake activity, some zones with above average seismic activity can be identified in Hungary. They are mainly located in the western and central part of the country, whereas the level of seismicity in the northeastern part of Hungary is rather low. The map of the expected PGA with a 90% probability of non-exceedance in 50 years (475-year return period) for the Pannonian region compiled by Tóth et al. (2006) shows that the expected PGA is 0.068g in the vicinity of the Baradla cave and 0.086g near the Hajnóczy cave.

Figure 2. Topographic map with major structures in Bulgaria and the location of caves. Faults: 1: normal; 2: strike–slip; 3: fault with unclear type. The capital letters indicates the names of the faults (Kotzev et al. 2006).

Bulgaria is located in the central part of the Balkan Peninsula. The Bulgarian territory is a part of the Alpo-Himalayan seismic belt, which is characterized by a high level of seismic activity. This area of the Peninsula represents a part of the intensively deforming continental marginal zone of Eurasia. Considering seismological and tectonic criteria, the Bulgarian territory has been subdivided in three main seismic regions: Northeastern, Srednogorie and Rila-Rhodopes (Grigorova et al. 1979, Orozova and Slejko 1994). The Srednogorie region includes two major seismogenic zones: Sofia zone and Maritza zone. Varteshkata and Elata caves are situated in Sofia seismogenic zones. The Sofia zone is characterized by moderate earthquakes ($6.0 =< M < 7.0$). The Rila-Rhodopes region, covering SW Bulgaria, is characterized by the highest seismic activity, because this zone involves the Kresna seismic zone. Snezanka and Eminova caves are situated in Rila-Rhodopes region, but far from the epicentre of the strongest earthquake in Bulgaria in Kresna zone. The Rhodope domain (Figure 2) has fewer seismic events. According to the map for 1 kyr return period in Bulgarian building code (1987) Elata and Snezanka caves are placed in the region with a_g = 0.15-0.25g and Varteshkata and Eminova cave is in the region with a_g = 0.10g.

3 THE CAVES

For descriptions about caves see papers: Szeidovitz et al. (2008a, 2008b), Gribovszki et al. (2008). It is known that, with the deepening of the caves, the attenuation of seismic waves rises (Becker et al. 2006). Therefore, it is important to mention that the caves where the investigated speleothems stand are situated at shallow depth. The Olimposz Hall in the Baradla cave is located at 35–40m below surface. The Ördög-lik Hall of Domica Cave is also in shallow depth below the surface. The Hajnóczy cave can be found in 60m depth beneath the surface. In case of the caves in Bulgaria: Varteshkata and Elata caves are 40-50m from the surface, and Snezanka and Eminova caves are not farther than 20-30m from the surface.

4 NON-INTRUSIVE IN SITU MEASUREMENTS OF SPELEOTHEMS IN CAVES

Considering that the in situ measurements had to be done non-intrusively, we confined ourselves only to determine the dimensions and fundamental frequency (FF) of speleothems. To measure FF small amplitude forced vibration was obtained by a gentle hit using one's hand or a rubber hammer. The horizontal acceleration of the speleothem was registered by an SM6 geophone (its FF is 10Hz) and a SIG SMACH SM-2 digitiser. The power spectral density of the vibration has been determined by fast Fourier transform. The photos of investigated stalagmites, the measured traces and their spectra (power spectra density (PSD)) are displayed in Figures 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14. Table 2 shows, the horizontal and vertical dimensions of the seven studied stalagmites, the height and average diameter ratio and the in situ measured FF (f_0). The characteristic diameters ($D_{Average}$) of the more or less cylindrically shaped stalagmites fall in the range of 4.1 and 11.6cm. Their height varied from 1.17 to 5.10m. Consequently, the height/diameter ratios in five cases were exceptionally large ($23 \leq H/D \leq 125$), and in two cases (Elata and Snezanka caves) smaller. It is understandable since Elata and Snezanka caves located at a territory with higher seismic hazard. The measured FF of the investigated stalagmites fall in the range of 1.4 – 19.9Hz.

Table 2. The dimensions of the investigated stalagmites in several caves in Hungary, Slovakia and Bulgaria and their in situ measured natural frequencies

	H [cm]	$D_{Average}$ (D_{min}-D_{max}) [cm]	H/D	Measured Natural Frequency, f_0 [Hz]
Baradla Olimposz	510	8.5 (7.5-10.0)	51-68	1.4
Hajnóczy	360	5.0	72	4.0
Domica Ördög-lik	500	5.0 (7.2-4.0)	69-125	2.0
Varteshkata	365	11.6 (10.0-13.1)	28-36	4.5
Elata	237	11.0 (8.3-13.7)	13-29	17.8
Snezanka No. 2	140	11.0 (8.3-13.7)	10-17	19.9
Eminova	117	4.1 (3.0-5.1)	23-39	17.5

Although dripstones are seemingly simple structures, their tensile strength, age and FF changes during their formation. In some dripstones their FF may rise as high as the frequency domain of the earthquakes. If FF is below 20Hz (it is the approximate upper limit of the frequency range of nearby earthquakes), then resonance can occur, and we have to take into account the dynamic amplification (Lacave et al. 2004). This is the situation in each stalagmite here in this paper. The resonance means that in reality the dripstones would break at a lower value of HGA than the computed one.

It is interesting to note that our results of in situ FF measurements are very close to the ones gained by Lacave et al. (2000, 2004) (Figure 15). They show the estimated FF values for speleothems of different type, based on in situ measurements in French caves. The measured FF for our stalagmites in Varteshkata, Snezanka, Baradla, and Eminova caves place almost on the curves describing FF of stalagmites with diameters of 5 and 10cm in accordance with the average diameters of our investigated stalagmites. The measured FF for our stalagmites in Hajnóczy and Domica fall between the two, previously mentioned curves. We can conclude that the frequency values determined in the two studies are in very good agreement in spite of the different measuring techniques.

Figure 3. Stalagmite(5.1m) in Baradla cave, Olimposz Hall

Figure 4. Stalagmite(5m) in Domica cave, Ördög-lik Hall

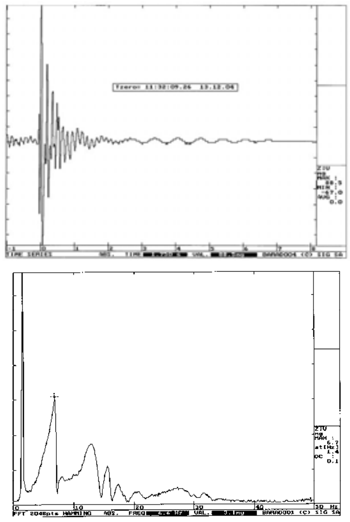

Figure 5. Oscillation and power spectra density (PSD) of stalagmite(5.1m) in Baradla cave

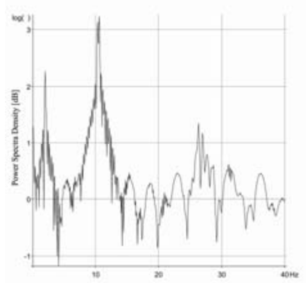

Figure 6. PSD of stalagmite(5m) in Domica cave

Figure 7. Stalagmite(3.65m) in Varteshkata

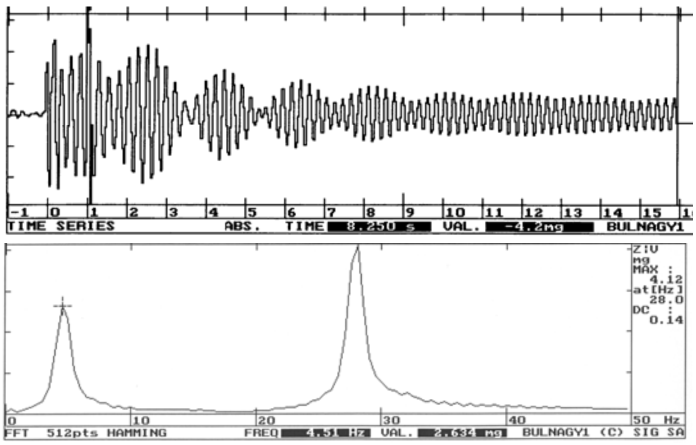

Figure 8. Oscillation and PSD of stalagmite(3.65m) in Varteshkata

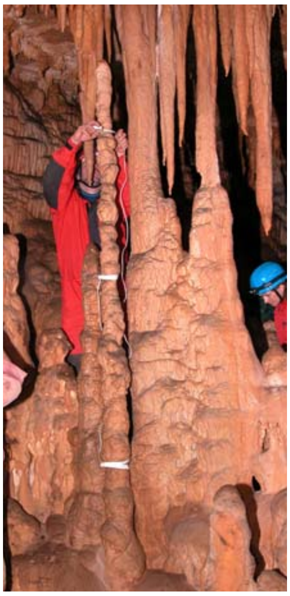

Figure 9. Stalagmite(2.37m) in Elata cave

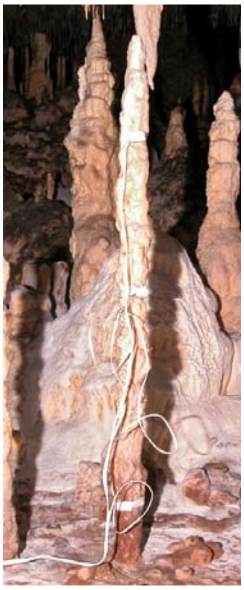

Figure 11. Stalagmite(1.4m) No.2 in Snezanka cave

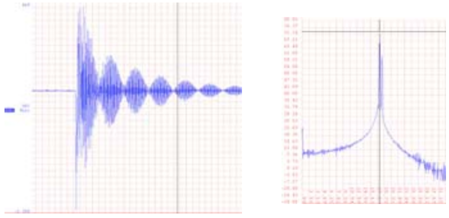

Figure 10. Oscillation and PSD of stalagmite(2.37m) in Elata cave

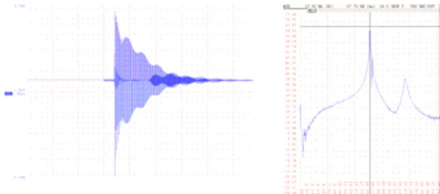

Figure 12. Oscillation and PSD of stalagmite(1.4m) No.2 in Snezanka cave

Figure 13. Stalagmite(1.17m) in Eminova cave

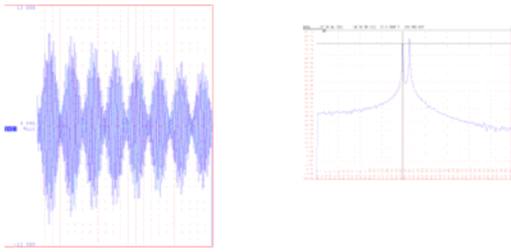

Figure 14. Oscillation and PSD of stalagmite(1.17m) in Eminova cave

5 OSCILLATION OF STALAGMITES – THEORETICAL CONSIDERATIONS

In our modeling the stalagmites were considered as vertical cylinders of height H and diameter D with a circular cross section. We supposed that the bottom of the cylinders is firmly fixed to the ground and the top can move freely. The material of the stalagmites was considered homogenous.
The natural frequency (FF) of a stalagmite (Szeidovitz et al. 2008a) can calculate by the cantilever beam theory:

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

where E is the Young's moduls, ρ is the density of the speleothem.

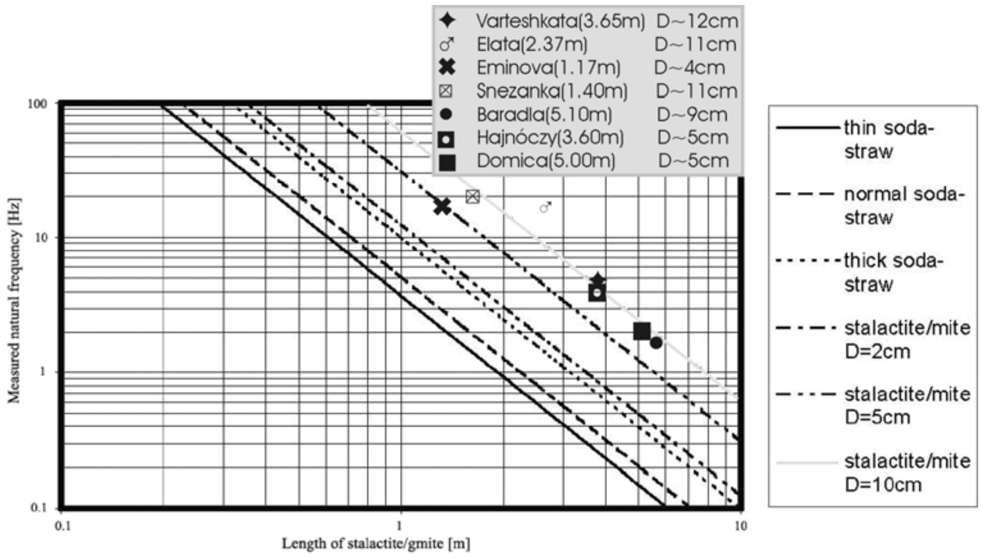

Figure 15. Graph for a rough estimation of the natural frequency of a speleothem as a function of its type, length and diameter based on in situ measurements in French caves in Lacave et al. (2000, 2004) in additionally the results for our in situ measurements in Varteshkata, Elata, Snezanka, Eminova, Baradla, Hajnóczy and Domica caves are shown.

The static, horizontal ground acceleration (HGA) resulting in failure (Cadorin et al. 2001):

$$a_g = \frac{D\sigma_u}{4\rho H^2} \quad (2)$$

where σ_u is the tensile failure stress of the stalagmite. This equation does not take into consideration the phenomenon of resonance. It can be seen that both FF and HGA resulting in failure depend on the geometrical properties of the stalagmite in the same way, i.e. they are proportional to D/H^2.

6 MECHANICAL PROPERTIES OF STALAGMITES

Laboratory measurements were performed on samples originating from stalagmites that was found lying broken on the ground of the investigated caves. Tensile failure stress (σ_u) was measured by Brazilian test, while dynamic Young-modulus (E) was determined by using ultrasound velocity propagation values. Table 3 (columns 4, 5 and 6) shows the summarized results of mechanical laboratory measurements of stalagmite-samples and the results of theoretical calculations: theoretical FF and the theoretical minimum HGA needed to break the given stalagmite (columns 7 and 8).

The observed and theoretical FF (Table 2) differ by a factor of 2.5-0.5. The difference probably comes from the used approximations, as the shape of the speleothems more or less differ from the shape of a cylinder, their material is not homogeneous, and the material mechanical parameters are based on measurements performed on specific stalagmite-samples, which are in some case originated from a different cave.

Based on Table 3, we can conclude that, for the investigated speleothems in the Baradla, Domica and Hajnóczy caves, the HGA values needed to break them are between 0.055, 0.059 and 0.065g, which can arise even in the case of moderate sized earthquakes. The computed a_g values for the studied stalagmites in Varteshkata and Elata caves fall in the range of 0.147g and 0.317g, which can arise even in case of middle-sized earthquakes, in Snezanka and Eminova caves fall in the range of 1.58g and 1.34g, such a high acceleration values can arise in case of strong earthquakes.

Table 3. The results of mechanical laboratory measurements of stalagmite-samples lying broken on the ground and the results of theoretical FF and theoretical minimum HGA needed to break the given stalagmite

	H [cm]	$D_{Average}$ [cm]	dynamic Young's modulus E, [GPa]	Density [gr/cm^3]	Tensile failure stress σ_u, [MPa]	Theoretical Natural Frequency f_0, [Hz]	Theoretical a_g [m/s^2]
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Baradla, Olimposz	510	8.5	20.8±5.9 data from Baradla	2.39±0.16 data from Baradla	1.62±0.48 data from Baradla	1.3	0.55
Hajnóczy	360	5.0	---	---	---	1.6 data from Baradla	0.65 data from Baradla
Domica, Ördög-lik	500	5.0	23.6±4.0 data from Domica	2.35±0.12 data from Domica	2.75±0.56 data from Domica	0.9	0.59
Varteshkata	365	11.6	53 data from Varteshkata	2.40 data from Varteshkata	1.62±0.42 data from Elata	5.6	1.47
Elata	237	11.0	---	2.50±0.08 data from Elata	1.62±0.42 data from Elata	12.4 using E=53GPa	3.17
Snezanka No. 2	140	11.0	----	2.32±0.15 data from Snezanka	2.61±0.28 data from Snezanka	37.0 using E=53GPa	15.78
Eminova	117	4.1	---	2.14±0.25 data from Eminova	3.83±0.81 data from Eminova	20.5 using E=53GPa	13.40

7 SAMPLING AND AGE DETERMINATION

We took core-samples from the stalagmite of 5.1m high (Figure 3) in Olimposz Hall of Baradla cave at different heights to determine its age and rate of growth. Details about the sampling and the used age determination methods are written in Szeidovitz et al. (2008a). Age determination of the investigated stalagmite is important, because it is necessary to know how long the time period is since their shape is unchanged. (On seismic hazard maps for a territory the expected PGA is given for a time period and for a certain probability.) Our measurements show that, below the height of 390 cm (measured from the bottom of the speleothem), the ages become younger with the increasing height of the sample origin; therefore, the dating results are in good agreement with the formation mechanism of the stalagmites. As a conclusion of age determination we can suppose that stalagmite in Olimposz Hall of Baradla cave has not been changed significantly during the past 70 kyr. We took two core-samples as well from a 2.26 m high stalagmite standing at Szűzfolyosó of Domica cave at two different heights (at the top and at the bottom of it) to determine its age and rate of growth. (Because of the high risk of vulnerability of in situ measured stalagmite in Ördög-lik Hall it was impossible to take core-samples from it.) The bottom of stalagmite at Szűzfolyosó is about 115kyears old, while the top of it is recent.

Similar investigations have been carried out as well for stalagmites standing in Bulgarian caves (Szeidovitz et al. 2008b, Gribovszki et al. 2008). It can be concluded from the age determination that the rates of growth of these stalagmites are high, they developed during a few kyr. This means that we can order to the determined HGA resulting in failure only very short time period, some 100 years, however in map of Bulgarian building code (1987) the values are determined for 1 kyr return period.

8 CONCLUSION

Stalagmites with large height/diameter ratio (H/D>50) have been found in two Hungarian caves, and in the Domica cave, Slovakia. Stalagmites with moderate H/D ratio (40>H/D>20) have been found as well in two Bulgarian caves (Varteshkata and Eminova), these two caves are situated in moderate seismic hazard area, while in area with higher seismic hazard such a slim stalagmite (H/D>30) could not be found. We determined by in situ measurements fundamental frequency (FF) of seven speleothems of the Baradla, Hajnóczy (Hungary), Domica (Slovakia), Varteshkata, Elata, Snezanka and Eminova (Bulgaria) caves, and in laboratory, the material properties (the density, the Young's modulus and the tensile failure stress) of stalagmite specimens have been measured. Based on a simple mechanical model (cantilever beam theory), the theoretical FF (f_0) and the horizontal ground accelerations (HGA) values resulting in failure (a_g) have been calculated for the stalagmites.

Based on Table 3, we can conclude that, for the investigated speleothems in the Baradla, Domica and Hajnóczy caves, the measure of HGA needed to break them are between 0.055g, 0.059g and 0.065g, which can arise even in the case of moderate sized earthquakes. As the FF of these stalagmites is in the frequency range of nearby earthquakes; the failure acceleration can be even smaller because of the resonance effect. This agreement, together with the results of age determination, allows us to estimate an upper limit on prehistoric HGA. On the basis of our measurements and theoretical calculations, we can assume that the geological structures close the Baradla and Domica cave did not generate paleoearthquakes producing HGA larger than 0.055g in the last 70 kyr in case of Baradla cave and 0.065g for Hajnóczy cave. These acceleration levels are lower for all these three caves than the PGA value determined by Tóth et al. (2006) (0.068g for Baradla and Domica, 0.086g for Hajnóczy) for a much shorter period of time, and evidently, the expected PGA would be even greater for a 70 kyr.

The computed a_g values for the studied stalagmites in Varteshkata and Elata caves fall in the range of 0.147g and 0.317g, which can arise even in case of middle-sized earthquakes. As in most cases the FF of the stalagmites is in the frequency range of nearby earthquakes, the failure acceleration can be even smaller because of the resonance effect. The calculated maximal static HGA in case of both caves are a little bit higher than what we get from the Bulgarian building code. The computed a_g values for the studied stalagmites in Snezanka and Eminova caves fall in the range of 1.34g and 1.58g, such a high acceleration values can arise in case of very-sized (strong) earthquakes. The maximal HGA calculated by us in case of both caves are much more higher than what we get from the Bulgarian code.

9 PLANS FOR THE FUTURE, STALAGMITE-INVESTIGATIONS IN AUSTRIA

Recently we started preparing a catalogue of caves containing intact stalagmites suitable for our investigations for the territory of the Eastern Alps. "Suitable stalagmites" means in this context that it can be assumed by the dimensions of the stalagmites (height/diameter ratio > 30) that the stalagmite could be broken by the excitation of a lower HGA value than the expected peak ground acceleration estimated for the territory of the cave location. According to the earthquake hazard map of Austria (Giardini et al. 1999), peak ground acceleration with a 10% chance of exceedance in 50 years, corresponding to a return period of 475years in the Eastern Alps is 1-1.5m/s^2 is the expected peak ground acceleration. Taking into account our previous observations a stalagmite with similar shape as the one in Varteshkata cave, present in this paper (height=3.65m, average diameter=10cm), or a slimmer one is suitable for estimating the upper limit on horizontal prehistoric peak ground acceleration in Eastern Alps, assuming that the mechanical properties of stalagmites in Eastern Alps do not differ much from our previous results. We are acquainted with dripstone caves (Katerloch, Lurgrotte Semriach), in which there are stalagmites suitable for our investigations.

Furthermore the movement and failure of stalagmites subjected to earthquake excitation are planned to analyze numerically. The planned model computation takes into account the real shape of the stalagmite as a 3D structure consist of solid elements. To calculate the behaviour of the stalagmite under seismic action a normalized response spectra curve from building code can be used. Similar model computation had been done previously in case of Varteshkata stalagmite in Bulgaria by civil engineers from Sofia. Now we are looking for colleagues from structural engineering to model numerically the movement and failure of stalagmites subjected to earthquake excitation.

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