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MEASUREMENT OF NATURAL FREQUENCIES AND DAMPING OF SPELEOTHEMS

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SUMMARY

Broken speleothems (stalagmites, stalactites, soda-straws, etc.) can be interpreted as an indicator of past earthquakes. The dating of such events, up to several thousands of years, could then allow an evaluation of the seismic activity in an area, up to ages much older than that is possible from historical catalogues. This is of particular interest for the determination of long return-period events. One might also consider unbroken speleothems as an indication that no event greater than a certain level has occurred in the region. In order to evaluate the vulnerability of speleothems from earthquakes, it is necessary to know the range of their natural frequencies. However, there had been, up to now, no experimental in-situ measurements made to obtain these frequencies. The work presented here was aimed at the measurement of the fundamental natural frequencies and the damping of a representative population of speleothems. Measurements were made in the caves of Choranche and Antre de Vénus, in the Vercors Mountains (France), using a high-resolution laser interferometer. This study made it possible to show that most of the speleothems do not undergo dynamic amplification phenomena of the seismic motion, since their fundamental natural frequencies are higher than the range of seismic excitation. Only thin and long speleothems (such as long soda-straws) may suffer amplification phenomena. A fundamental frequency higher than the seismic frequencies means that the speleothem moves, with its basement, as a rigid structure. Consequently, most of the broken speleothems are a direct indicator of the peak ground acceleration. In order to use "speleoseismic" traces for seismic hazard assessment in a given area, the magnitude of the corresponding earthquake has to be evaluated. Further studies are proposed with the aim of a quantitative estimate of the confidence level that could be reached in the determination of the magnitude of "speleoseismic" events.

INTRODUCTION

Broken speleothems can be considered as evidence of past earthquakes. Some studies have already been conducted in order to find such traces, and if possible to date the event that could have been responsible for the observed breaks. Postpischl et al. [1991] and Gilli [1995] give pioneering examples of such investigations. Further studies were also conducted by Delange et al. [1998]; Gilli et al. [1998] and Menichetti [1998], for example. A general state of the art in this field is given by Forti [1998].

The age of broken speleothems, often of thousands of years, could, in principle, make it possible to describe the seismic history of a region up to much more ancient times than can be achieved with historical seismicity studies. The inverse approach can also be of great interest: non-broken speleothems could be interpreted as the non-occurrence of earthquakes of a certain level during such a period, in the region. In both cases, a major question arises concerning the uncertainty in the determination of the intensity of such a minimum or maximum paleo-earthquake, from broken or unbroken speleothems.

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In order to determine the behaviour of speleothems under seismic action, it is necessary to have information about the natural frequency band of such speleothems. However, no *in-situ* measurement campaign has been conducted so far. The first aim of the present study was to measure natural frequencies of a characteristic population of speleothems. This group of objects has to be characterised by different types, shapes and sizes of the concretions but also by several samples of each category (similar shape and size). Measurements were conducted in two different caves, located in the karstic Vercors Massif (France): the "Choranche" cave and the "Antre de Vénus" cave. The second aim of this study was to measure the coefficient of critical damping for each of the speleothems considered. This was done using a time history record of the free oscillations of the speleothem.

DESCRIPTION OF THE CHOSEN CAVES

The first cave (Choranche) is located in a deep gorge, under a 250 to 300 hundred metre high cliff of limestone. This cave presents the following advantages:

- It contains a great variety of speleothems (stalactites, stalagmites, etc.), and particularly a lot of soda-straws (very thin tube stalactites).
- The Choranche cave has already been studied from geological and chemical points of view [Delannoy, 1997]. Many instruments are already installed in the cave, and an "underground laboratory" is now being set up.
- Because it is also a tourist cave, it offers the opportunity of easy access and a comfortable environment for the measurements (paths to carry the equipment, electricity, etc.).

The "Antre de Vénus" cave (a non-equipped cave) was also chosen to give an idea of the variability in the results from different caves. This cave, located near the surface, is characterised by a narrow entrance gallery, followed by a 14-m deep pit. The cave then continues as a large gallery with many concretions, in which the measurements were made, at a distance of about 150-m from the entrance. Despite the difficulty in carrying the equipment in natural underground conditions, this cave is an interesting site for scientific research because:

- It presents a wide variety of speleothems (soda-straws, long stalactites)
- Many geological and karstological studies have also been conducted in this cave [Caullireau and Caillault, 1991; Caullireau et al., 1991].

METHODOLOGY

Natural frequency measurements were made with a Polytech OFV 3001 high-resolution laser interferometer. It consists of a laser generator connected to an amplifier and a de-modulator, followed by a filter box. The whole instrument set is connected to an oscilloscope used for data acquisition, processing and storing. A small piece of reflecting tape had to be stuck at the end of the speleothem to be measured, in order to ensure a good reflection of the laser ray. The speleothem was then slightly excited, with a light breath (for the fragile soda-straws) or a light hit with a rubber stick. The velocity of the speleothem extremity was recorded as a function of time. Then, an average Fourier spectrum was calculated from 12 recordings. These spectra show the fundamental resonance frequency and, in some cases, frequencies of higher modes.

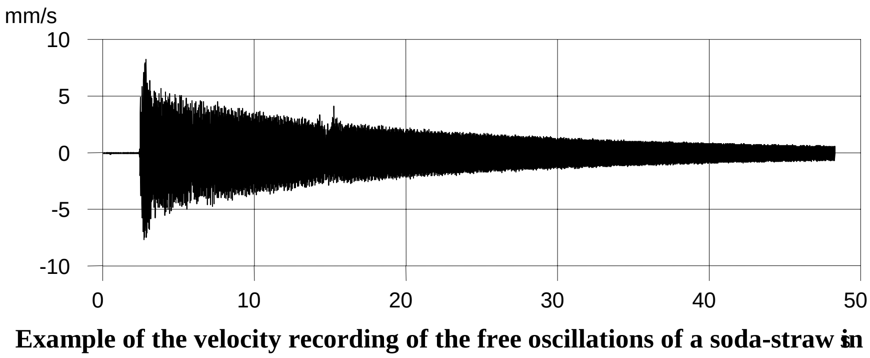

Figure 1 : Example of the velocity recording of the free oscillations of a soda-straw in the "Antre de Vénus" cave.

The damping of each speleothem is calculated from the oscillation time history, as follows :

$$D = \frac{1}{2\pi \cdot N} \cdot \ln\left(\frac{A(i)}{A(i+j)} \right)$$

where i and j are the time indices to which the amplitude values $A(i)$ and $A(i+j)$ correspond, N being the number of periods considered. D is the viscous equivalent damping, which will be expressed as a percentage of the critical damping, as commonly done in earthquake engineering. The critical damping (D = 100 %) corresponds to the limit of the oscillatory behaviour. Beyond this limit (D > 100%) oscillations are no longer possible. The value commonly used to express standardised response spectra is 5 %.

RESULTS

In the "Choranche" cave, 12 speleothems were measured (6 stalagmites between 34 and 82 cm, 3 soda-straws from 8.5 to 28 cm long, 3 stalactites from 25 to 45 cm long). The characteristics (length and diameter) and results obtained (natural frequencies and damping) for all the speleothems measured in the "Choranche" cave are listed in Table 1. In the "Antre de Vénus" cave, 8 speleothems have been measured (2 soda-straws from 70 to 80 cm long, 4 stalactites between 64 and 89 cm long, 1 "giant" stalactite of 3.5 m in length, 1 column of 78 cm in length). Characteristics and results about these speleothems are presented in Table 2.

For each measured speleothem it is possible to see at least two and occasionally as many as four frequency peaks. These can be interpreted either as fundamental modes of vibration in the direction of the principal axes ($f_0^{(1)}$ and $f_0^{(2)}$) or as higher modes ($f_i^{(1)}$ and $f_i^{(2)}$). In most cases, measured frequencies appeared to be much higher than the frequency range of seismic excitation. All measured frequencies are between 50 and 700 Hz, except for the two soda-straws measured at the "Antre de Vénus" cave (FIS1 and FIS2, 66 and 79 cm long), which have a natural frequency around 20 Hz. These frequencies correspond to the upper range of a seismic excitation (roughly between 0.1 and 30 Hz).

Table 1 : Characteristics of the speleothems measured in the "Choranche" cave, and associated results (natural frequencies and damping)

Name	**Type**	**LENGT**	**DIAMET**	**$f_0^{(1)}$ [Hz]**	**$f_0^{(2)}$ [Hz]**	**$f_1^{(1)}$ [Hz]**	**$f_1^{(2)}$ [Hz]**	**D [%]**
STM1	stalagmite	48	5-12	175	182.5	(277)	----	1.27
STM2	stalagmite	82	9-12	115	122.5	----	----	0.26
STM3	stalagmite	37	6.5	78	100	(230)	----	7.6
STM4	stalagmite	55	4-5	100	163	----	----	7.6
STM5	stalagmite	34	6-8.5	376	433	----	----	1.70
STM6	stalagmite	45	5.5-6.5	196	209	----	----	0.91
FIS1	soda-straw	8.5	0.5	666	700	----	----	0.04
FIS2	soda-straw	10	0.7	492	531	----	----	0.11
FIS3	soda-straw	28	0.7-0.8	65	70	448	----	0.42
STT1	stalactite	25	1-5	435	766	----	----	6.0
STT2	stalactite	25	1.6	173	205	----	----	0.15
STT3	stalactite	45	0.8-3	53	118	----	----	1.55

Table 2 : Characteristics of the speleothems measured in the "Antre de Vénus" cave, and associated results (natural frequencies and damping)

Name	**Type**	**LENGTH [cm]**	**DIAMETER [cm]**	**$f_0^{(1)}$ [Hz]**	**$f_0^{(2)}$ [Hz]**	**$f_1^{(1)}$ [Hz]**	**$f_1^{(2)}$ [Hz]**	**D [%]**
STT1	stalactite	64	3.5	----	----	207	241	0.16
STT2	stalactite	74	3.5	----	----	158.5	195	0.11
STT3	stalactite	89	4	----	----	141	156	0.04
STT4	stalactite	81	3.2	----	----	133.5	167.5	0.03
STT5	stalactite	350	30-60	97	116	(129)	----	0.20
COL1	column	78	6	355	394	----	----	0.26
FIS1	soda-straw	66	0.5-1.5	22.2	24.2	155	173	0.12
FIS2	soda-straw	79	0.8-1.7	23	----	82	----	0.04

Regarding the damping measured from the time histories, it appears that most of the speleothems have a very low damping value, between 0.03% and 1.7%. Only two stalagmites (STM3 and STM4) and one stalactite (STT1) in the "Choranche" cave, have a damping value of 6 to 7.6%. This is probably due to small splits between the speleothem and its basement. It seems that the damping value for each speleothem is strongly linked to the type of fixing on the rock (calcite deposit on the rock or not, clay deposit for the stalagmite, etc.).

INTERPRETATION

Using the measured natural frequencies, we calculated the Young's modulus (E) of each speleothem. In the simple case of a prismatic cantilever beam, the natural frequency is given by :

$$f_i = \alpha_i \cdot \sqrt{\frac{E \cdot I}{\mu \cdot l^4}}$$

with $\alpha_0 = 0.560$, $\alpha_1 = 3.57$, $\alpha_2 = 9.81$, etc. I, the moment of inertia, and μ, the mass per unit length are given by:

$$I = \left(\frac{\pi}{64}\right) \cdot \left(D^4 - d^4\right) \qquad \mu = \left(\frac{\pi}{4}\right) \cdot \left(D^2 - d^2\right) \cdot \rho$$

where D is the external diameter and d is the internal diameter ($\neq 0$ for the soda-straws). Young's modulus can therefore be written as:

$$E = \left(\frac{f_0}{\alpha_0}\right)^2 \cdot \mu \cdot \frac{l^4}{I}$$

It is observed that natural frequencies are inversely proportional to the squared length (this is obvious from the f_i-formula above), i.e.:

$$f_i \propto \frac{1}{l^2}$$

For stalactites and stalagmites, $I \propto D^4$ and $\mu \propto D^2$, therefore:

$$f_i \propto D$$

It is clear that the above formulas are valid only for the speleothems with a roughly prismatic and regular shape. E was calculated for "acceptable" speleothems. A density value of $\rho = 2600$ kg/m^3 was taken for the calcite of the concretions [Kourimsky et Tvrz, 1983]. The resulting values of Young's modulus are quite high (from 37 to 72 kN/mm^2 in "Choranche" and 28 to 47 kN/mm^2 in "Antre de Vénus"), slightly higher than for a very good quality concrete. These values seem to be slightly lower for:

– soda-straws, in comparison with stalactites and stalagmites,
– concretions of the "Antre de Vénus" cave, compared to those of the "Choranche" cave.

The total number of measured objects is not large enough to draw final conclusions from this observation. However, in order to make approximate estimations, mean values are used :

– $E = 4.10^{10}$ N/m^2 for soda-straws.
– $E = 5.10^{10}$ N/m^2 for stalactites and stalagmites.

Very elongated speleothems alone have natural frequencies in the seismic frequency domain. Table 3 gives fundamental frequencies for different types of speleothems with a length of 1 m, and also the lengths necessary to reach a natural frequency of 1 and 10 Hz, for the same speleothems.

Table 3 : Calculated fundamental frequencies for typical speleothems with a length of 1 m, and lengths necessary to reach a natural frequency of 1 and 10 Hz, for the same speleothems.

Type of speleothem	DIAMETER [mm]	Wall thickness [mm]	f_0(L=1m) [Hz]	L(f_0=10Hz) [m]	L(f_0=1Hz) [m]
Very thin Soda-straw	5	0.5	3.5	0.59	1.8
Normal Soda-straw	7	1	4.8	0.69	2.2
Thick Soda-straw	15	5	8.8	0.94	3.0
Stalactite	20	----	12.3	1.1	3.5
Stalactite (Stalagmite)	50	----	31	1.7	5.5
Stalagmite Stalactite	100	----	62	2.5	7.8

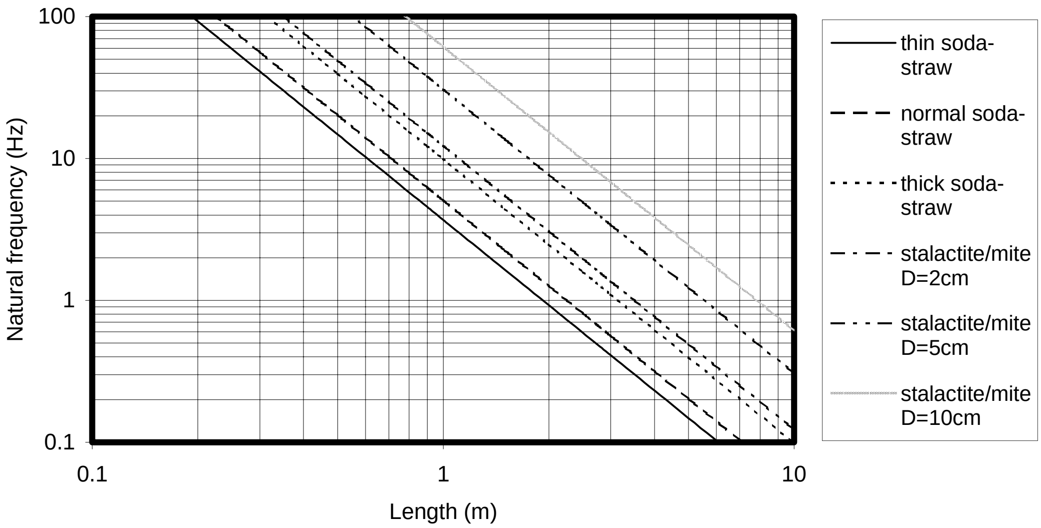

Figure 2 : Graph for a rough estimation of the natural frequency of a speleothem as a function of its type and length.

CONCLUSIONS

Most speleothems do not suffer dynamic amplification phenomena, because their natural frequencies are higher than the seismic frequency range (around 0.1 to 30 Hz). Only very elongated and thin speleothems (see Table 3) could undergo such amplification that might lead to their rupture.

A natural frequency which is higher than the seismic excitation range means that the speleothem moves as a rigid object together with its basement. It is in this case subjected to inertial forces, which correspond to the ground acceleration multiplied by the speleothem mass. Consequently, the speleothems must break at their roots and then could give an indication of the peak ground acceleration. Most of the broken speleothems that can be observed in caves show a rupture in different part which could be on a heterogeneity of the structure itself [Gilli et al., 1998]. Only very elongated speleothems could give information on the frequency content of past earthquakes.

Peak ground acceleration alone is a bad indicator of the magnitude of an earthquake, it would therefore be necessary to find traces of broken speleothems in a whole area in order to evaluate the damage extent. On the contrary, the inverse approach, which consists in excluding strong earthquakes in a given region, during the "life time" of present speleothems, seems to be more promising.

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