Estimating the upper limit of prehistoric peak ground acceleration using an in-situ, intact and vulnerable stalagmite from Plavecká priepast cave (Detrekői-zsomboly), Little Carpathians, Slovakia

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SUMMARY

Our observation is based on intact candlestick shape stalagmites (tall, vulnerable and cylindrical shape) in natural caves, which have survived several thousands of years. Their "survival" requires that horizontal ground accelerations have never exceeded a certain critical value during their "lifetime", namely over time periods of thousands years and more.

The aim of our study is to estimate the upper threshold for horizontal peak ground acceleration generated by paleoearthquakes, in other words to determine the maximum credible earthquake (M_{max}) that could occur in the last few thousand years. This information can complete input data for PSHA studies.

Here, in this extended abstract we present the most important results of our recently published paper about a case study of an intact, candlestick shape stalagmite. Furthermore some results of numerical and analogue modeling of a stalagmite's vibration have been showed briefly and some results of the computed depth-dependent attenuation of seismic waves as well.

Keywords: speleology, stalagmite, cantilever beam, natural frequency, peak ground acceleration, prehistoric earthquake, seismic hazard, speleoseismology

A stalagmite-based case study

strous effects. Obtaining an unbiased view of seismic hazard (and risk) is therefore very important.

Over the last years it has become clear that there are major gaps in the understanding of seismic hazard, and it has recently been pointed out (e.g., Anderson et al., 2011) that more information on the long-term hazard is needed. Precariously balanced rocks give important information, e.g. for the Western US, and the need for studies of speleothems has been especially pointed at, e.g. in the above-cited review paper. These formations survived all earthquakes that have occurred over thousands of years, depending on the age of the stalagmite. The new observations can provide information of maximum intensity (or magnitude) for long time scale as an input data for PSHA studies as well.

In Gribovszki et al. (2017) we presented the result of such a stalagmite-based case study from the Little Carpathians of Slovakia. A specially-shaped (candlestick type), intact and vulnerable stalagmite (IVSTM) in Plavecká priepast cave has been examined since 2013. This stalagmite is suitable for estimating the upper limit of horizontal peak ground acceleration generated by prehistoric earthquakes. The reason why this stalagmite is suitable is that it is tall, slim, its height-diameter ratio is more than 50, and its eigenfrequency falls into the frequency range of earthquakes occur nearby. Such stalagmites exist in this cave and in several other caves as well at many different places in this planet.

Our investigation consists of the following steps: (i) in-situ non-destructive determination of the natural frequency, the harmonic oscillations and measuring the dimensions of the IVSTM; (ii) laboratory measurements of the geomechanical and elastic properties (density, velocity of elastic waves propagating in stalagmite samples, and tensile failure stress) of stalagmite samples; (iii) calculation of the natural frequency and the harmonic oscillations of the IVSTM and the static horizontal ground acceleration value (a_g), which would break the IVSTM; (iv) age determination of core samples taken from speleothems; (v) determination of seismic wave attenuation with depth; (vi) construction of a critical horizontal ground acceleration curve going back into the past.

Fig. 1 presents the critical horizontal ground acceleration (HGA) value as a function of time (going back into the past) which we have determined from the stalagmite that we investigated in the Plavecká Priepast cave. E.g. at the time of Jókő event (1906) the critical HGA value cannot have been higher than 1 m/s^2, and 1.3 m/s^2 at the time of the assumed Carnuntum event (~340 A.D.), and three thousand years ago it must have been lower than 1.7 m/s^2.

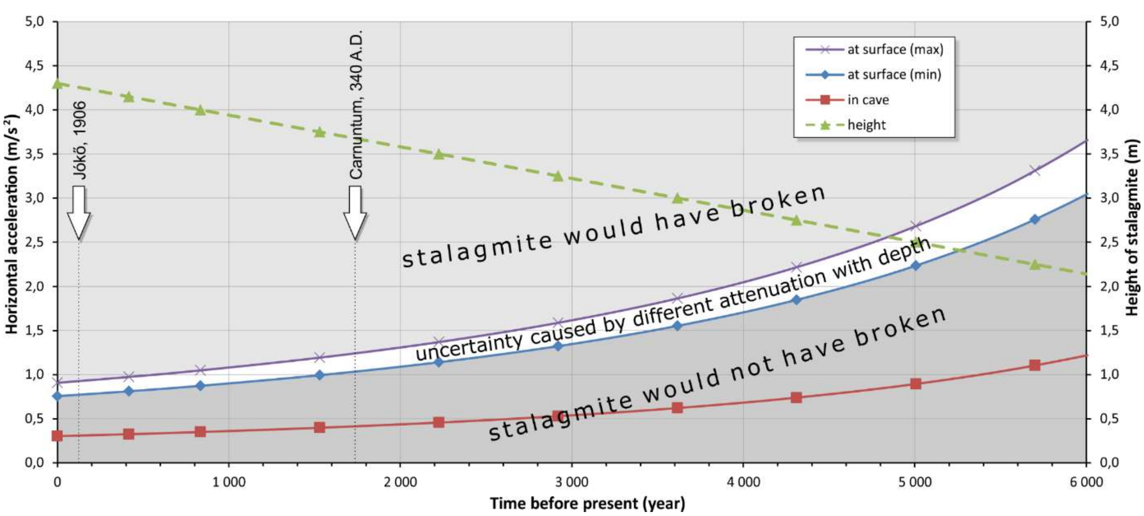

Figure 1.
Constraint on critical horizontal ground acceleration at the surface (purple and blue curves) and in the cave (red curve) provided by the height of the investigated stalagmite (green line) as a linear function of time going back into the past. The arrows show the ages of the assumed and real moderate size or large earthquakes occurred in the past. The uncertainty of the critical HGA at the surface is given by the white region.

In Gribovszki et al. (2017) we compared the effect of the Jókő earthquake (1906) on the location of the Plavecká priepast cave to the critical horizontal ground acceleration value provided by the stalagmite we investigated and claimed that the effect of Jókő earthquake (1906) is consistent with the critical HGA value provided by the stalagmite.

The approach used in Gribovszki et al. (2017) yields significant new constraints on the seismic hazard, as tectonic structures close to Plavecká priepast cave did not generate strong earthquakes in the last few thousand years. The results of this study are highly relevant given that the two capitals, Vienna and Bratislava are located within 40 and 70 km of the cave, respectively.

Progress in investigation of vulnerable stalagmites

The approach to determine to HGA by using stalagmites is very conservative. In order to get a more sophisticated threshold for HGA several new investigations have been performed for the last years.

Our method is particularly applicable for stalagmites in shallow caves, since seismic waves attenuate with depth (Becker et al., 2006). The results are thus the stricter the shallower the cave is. The IVSTM that we investigated in Plavecká priepast cave was found in a chamber which is in a shallow depth.

The effect of the depth of the cave needs to be taken into account (uncertainty on Fig. 1), and the more realistic this is done, the more accurate the constraint on seismic hazard becomes. Therefore model computation for determining the depth-dependent attenuation of seismic waves above the cave has been done (Győri et al., 2018). Our modeling results show that:

- the attenuation of seismic waves agrees well with determinations from earlier studies (amplitudes of seismic waves are 2.5-3 times higher at the surface than in the cave; see uncertainty on Fig. 1);
- larger thickness of limestone above the stalagmite yields higher attenuation;
- in case of stronger events the attenuation is higher;
- above 100 m thickness of limestone the waveforms, similar to Jókő event's waveform, suffer high attenuation at some of the resonant frequencies of the investigated stalagmite.

The pattern of oscillation of the investigated stalagmites should be fully understood since at the resonance frequency the stalagmites can break more easily than in the static case. During our cave observations we experienced that the harmonic oscillations of the investigated stalagmites split into two parts. Therefore we simulated the oscillation of a given stalagmite by setting up four simplified models of the stalagmite (Gribovszki et al., 2018). The eigenfrequencies of the different stalagmite models have been calculated numerically, by the finite element method, and compared with the measured in situ values. The splitting of eigenfrequencies was reproduced by the numerical model calculations, taking into account the asymmetric shape of the stalagmite.

In order to determine the critical value of HGA that would have made them failed at different stages of their growth, we need to understand the failure process of these intact and vulnerable stalagmites. More detailed information of the vulnerable stalagmites' rupture is required, and we have to know how much it depends on the shape and substance of the investigated stalagmite. Predicting stalagmite failure limits using numerical modeling is faced with a number of approximations, e.g. from generating a manageable digital model. Thus it seems reasonable to investigate the problem by analogue modeling as well (Gribovszki et al., 2017a; 2018a). The advantage of analogue modeling among other things is that nearly real circumstances can be produced by simple and quick laboratory methods. The samples representing a stalagmite were made from gypsum. These bodies were reduced-scale with a similar shape as the original stalagmite we investigated. During the measurements, we could change both the shape and the material and the time series of acting horizontal acceleration. Our analogue modeling results show:

- the stalagmite model samples have been broken at their base;
- the theoretically calculated eigenfrequency was almost the same as that we measured;
- a real seismic waveform of an earthquake (Umbria-Marche event, 1997) was able to break the stalagmite model samples. That means that not only a sharp peak that we calculated by theoretical equation can break the stalagmite;

Comparing the results from analogue and numerical modeling could improve the accuracy of long-term seismic hazard assessment.

Future plans:

- to measure the vibration of stalagmites in situ by Polytec portable digital vibrometer;
- to measure the depth-dependent attenuation in-situ (it has been already calculated for Plavecká priepast cave; see Győri et al., 2018);
- numerical modeling of the failure process of the stalagmites we investigated;
- numerical modeling of the stalagmite vibration using the real 3D shape of the stalagmite;
- in situ measurements for searching micro cracks and holes by acoustic tomography and ultrasound instruments (Hegymegi et al., 2016);

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