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3D finite element analysis of seismic response of a slender stalagmite

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Research Highlights

In the lecture planned for the Colloquium a finite element method (FEM) model of a slender, 4.3m stalagmite located in Plavecka Priepast cave (Figures 1 and 2) will be analyzed in detail with respect to its dynamic modal properties and seismic fragility. The main reason of this study is to gain long-term seismic hazard information for the surroundings of the investigated cave. A robust FEM model of the stalagmite will be presented and results of its modal properties and seismic response will be discussed as well.

Introduction

Typical fragile geological features (FGFs) are precariously balanced rocks studied in numerous papers (e.g., Brune, 2002, 1996, 1999; Ludwig *et al.*, 2015) or speleothems which represent separate branch of paleoseismology (e.g., Becker *et al.*, 2006; Ferranti *et al.*, 2019; Gribovszki *et al.*, 2018, 2017; Lacave *et al.*, 2004; Pace *et al.*, 2020; Paskaleva *et al.*, 2006) or serve other scientific studies (e.g., Engel *et al.*, 2020; Moseley *et al.*, 2014). Although the role of speleothems in calibrating seismic hazard is not straightforward (Gilli, 2005; Lacave *et al.*, 2004), their unique fragility is used in many papers aiming at verifying seismic hazard and, in particular, to put constraints on predicted Peak Ground Accelerations (PGA) of seismic hazard studies so that the observed speleothem was not damaged. This way the long-term seismic hazard studies for monumental structures like large dams or nuclear power plants can be better validated.

Typically, they are modeled as single-degree-of-freedom systems or other models of the simple, uniform vertical cantilever beams or other oscillating systems behaving like inverse pendulums. From a mechanical point of view, these models are very simplistic, while some of the fragile geological features are rather complicated in their size and shape. Besides, PGA is relatively a simple measure of seismic intensity because also other ground motion parameters may influence damage of the speleothems. Namely, these could be strong motion duration and spectral content of the seismic ground motion.

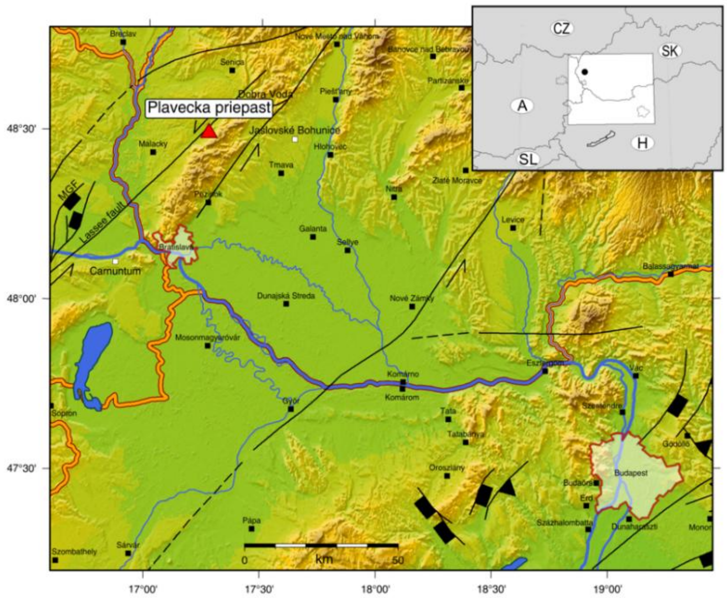

Figure 1. Location of the "*Plavecká Priepast*" stalagmite.

So far, there were only very few attempts to apply more detailed modeling methodologies to study the seismic motion of FGFs, particularly to use the FEM. The first such paper can probably be attributed to Hall (1996), who used 2D finite element stress modeling of statical equilibrium of six rock columns located in the Chiricahua Mountains, Arizona.

Recently Martin et al. (2020) carried out an analysis of ambient vibrations of so-called "Minaret" stalagmite 4.5 m high and with approximately 17-20 cm width, from Han-sur-Lesse cave located 80 meters underground in Wallonia, Belgium. The Authors used ultra-sensitive geophones to collect peaks values of amplitudes of extremely small ambient vibrations in three directions at the ground surface, at the stalagmite base, and at the height of 2.52 m.

Description of the FEM model and its calibration

In a recent paper (Zembaty *et al.*, 2023) a 3D FEM model of the 4.3m stalagmite measured in Plavecka Priepast cave (Figure 2) is presented. Results of its modal analyses based on data acquired using a 1-D, velocity sensor attached to that stalagmite at a height of 1.5 m are given in detail. The stalagmite is shown in Figure 2 together with a frame of Cartesian reference system and directions of applied seismic excitations.

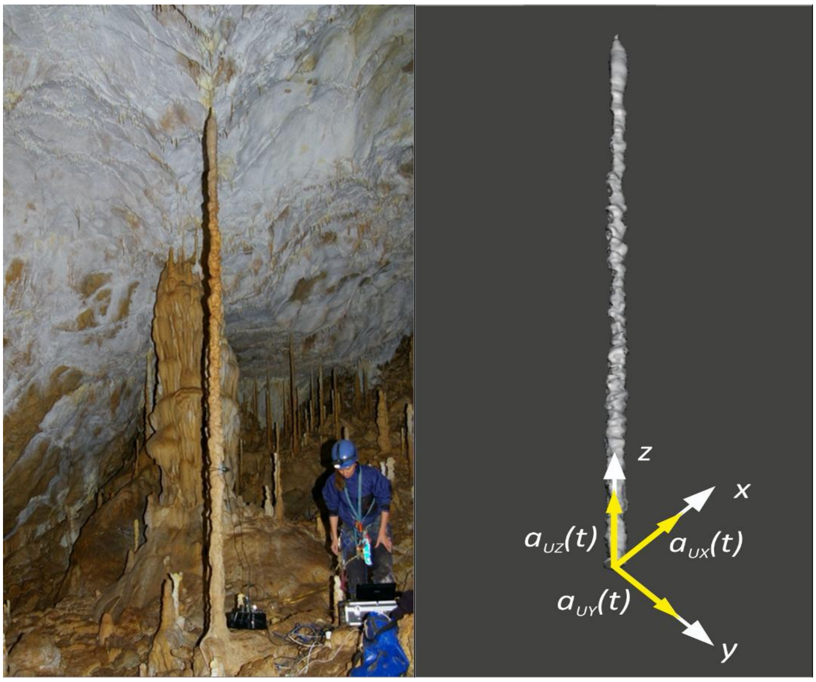

Figure 2. Photograph of 4.3m stalagmite in Plavecká Priepast cave and system of geometric axes applied in its analysis (*X-EW, Y-SN, Z-UP*) and its seismic accelerations (a_{UX}, a_{UY}, a_{UZ}).

The model consisted of 600 025 finite elements which generated 2 835 879 dynamic degrees of freedom and was used to compute seismic response to a selected, underground time history seismic record (for details see Zembaty *et al.*, 2023). In Figure 3 a fragment of the FEM mesh of the stalagmite is shown in detail. The whole view of the FEM model is also available at this link: https://z.zembaty.po.opole.pl/SupplementaryStalagmite.html

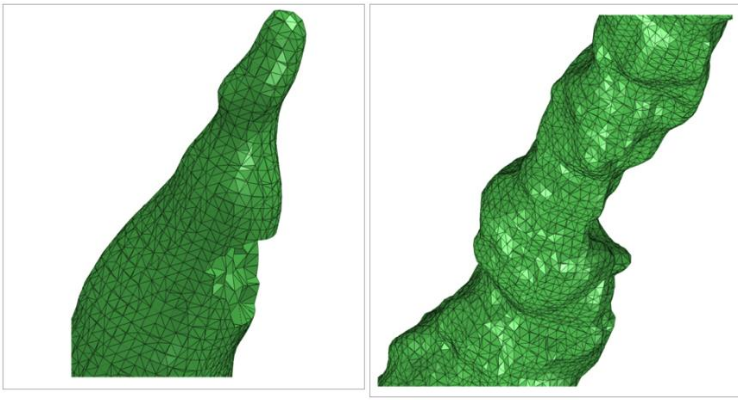

Figure 3. Details of Finite Element Method mesh of the modeled stalagmite in Plavecka Priepast cave

Results and conclusions

An analysis of the eigenproblem of the FEM model and subsequent Hilbert-Huang modal extraction (Zembaty *et al.*, 2023) gave natural frequencies and modal damping ratios presented in Table 1. Dynamic analyses of cantilever beams modeled as 3-dimensional bodies lead to conclusion that the natural frequencies of slender stalagmites will appear clustered in pairs. For these reasons the results of modal analyses are shown in Table 1 as "lower" and "upper" modes. Not all respective damping ratios could effectively be extracted, yet their extremely low values, well below 1% can easily be noted. The FEM model of the stalagmite was applied in seismic response analyses which led to a conclusion that the stalagmite may withstand seismic excitations with the ultimate horizontal peak ground velocity of 3.4 mm/s which is not far from the value obtained by Bottelin *et al.* (2020) for other slender speleothems (2.4 mm/s). For details of the seismic response analyses of the "Plavecka Priepast" stalamite see: Zembaty *et al.* (2023).

Table 1. Modal parameters of the "Plavecká Priepast" stalagmite.

Mode of vibration	**Natural frequency**	**ξ**
mode 1_{low}	2.96 Hz	-
mode 1_{up}	3.19 Hz	0.11 %
mode 2_{low}	14.50 Hz	0.14 %
mode 2_{up}	16.13 Hz	0.20 %
mode 3_{low}	35.72 Hz	0.20 %
mode 3_{up}	40.51 Hz	0.52 %

In May 2023 the Plavecka Priepast cave was revisited with an aim to improve the 3D vibration data acquisition of this and other stalagmites in this cave. The measurements were carried out simultaneously in two perpendicular planes using very accurate laser vibrometer (Polytec VibroGo). During the 8ICHISTEQ updated results of measurements of these stalagmites and their numerical analyses will be reported.

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