Seismic Vulnerability of a Slender Intact Stalagmite Standing in a Karstic Cave

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We are looking for constraints on long-term seismic hazard information. Constraints that we can calculate from vulnerable intact stalagmites.

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The observed objects

Our observation based on (and **ONLY** based on):

- **candlestick-type shape stalagmites**
  tall and cylindrical shape
- standing **intact** in natural caves,

(candlestick-type shape stalagmite:
special type objects
height/diameter ratio: 50-100 or larger
the diameter is more or less the same all along the vertical axis of the stalagmite)

Advantage of these objects:
vulnerable and several thousand years old.

The historical catalogues are short in geological time scale and incomplete (does not contain all of the EQs)

These objects "survived" all EQs. Their „survival" requires that horizontal accelerations have never **exceeded** a certain critical value over time periods of thousands years and more.

STM(4.3m) in Detrekői zsomboly cave (Plavecka priepast), Slovakia
Height ≈ 4.3 m; Diameter ≈ 8.5 cm; H/D ≈ 51

Method ---- Determining PGA_{up} by using the stals.--- PREVIOUSLY

Oscillation of stalagmites by simple theoretical calculations

The natural frequency of a stalagmite

Bernoulli-Euler Beam Theory

$$f_0 = \frac{1}{\pi}\sqrt{\frac{3.1ED^2}{16\rho H^4}}$$

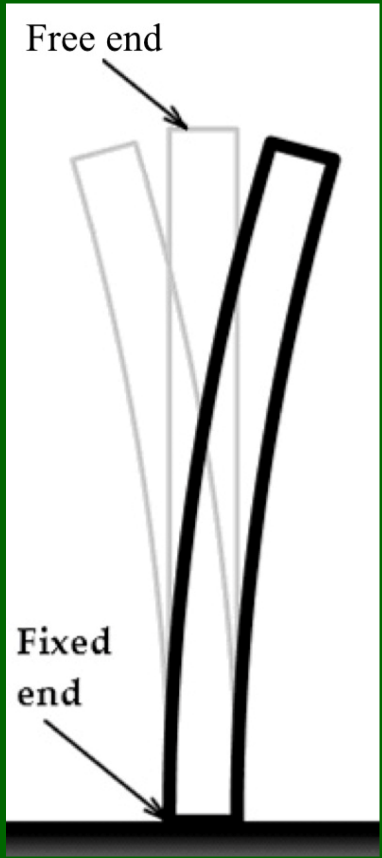
$$f_i = \alpha_i \sqrt{\frac{ED^2}{16\rho H^4}}$$

Kong et al. 2008

The static, horizontal ground acceleration resulting in failure

$$a_g = \frac{r\sigma_u}{2\rho H^2}$$

Cadorin et al. 2001

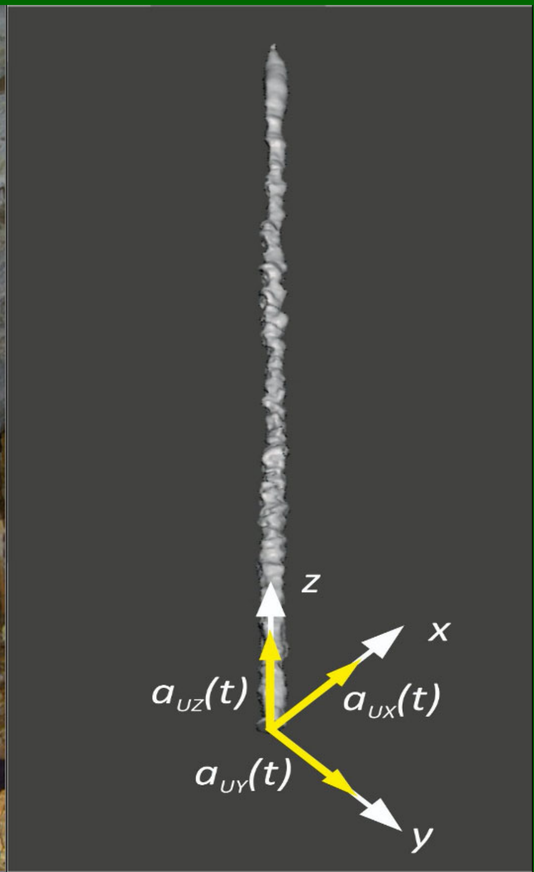


D: diameter
r: radius measured at the horizontal section of the cylindrical shaped stalagmite,
H: height of the stalagmite,
ρ: density of the stalagmite,
E: Young modulus,
σ_u: is the tensile failure stress of the stalagmite

Steps of the computation of stalagmite's seismic response

- A robust, fully three dimensional Finite Element Method model was prepared and calibrated from free vibration records by Hilbert-Huang modal extraction;

- The laser scan of the stalagmite with mm accuracy was used for constructing the FEM;



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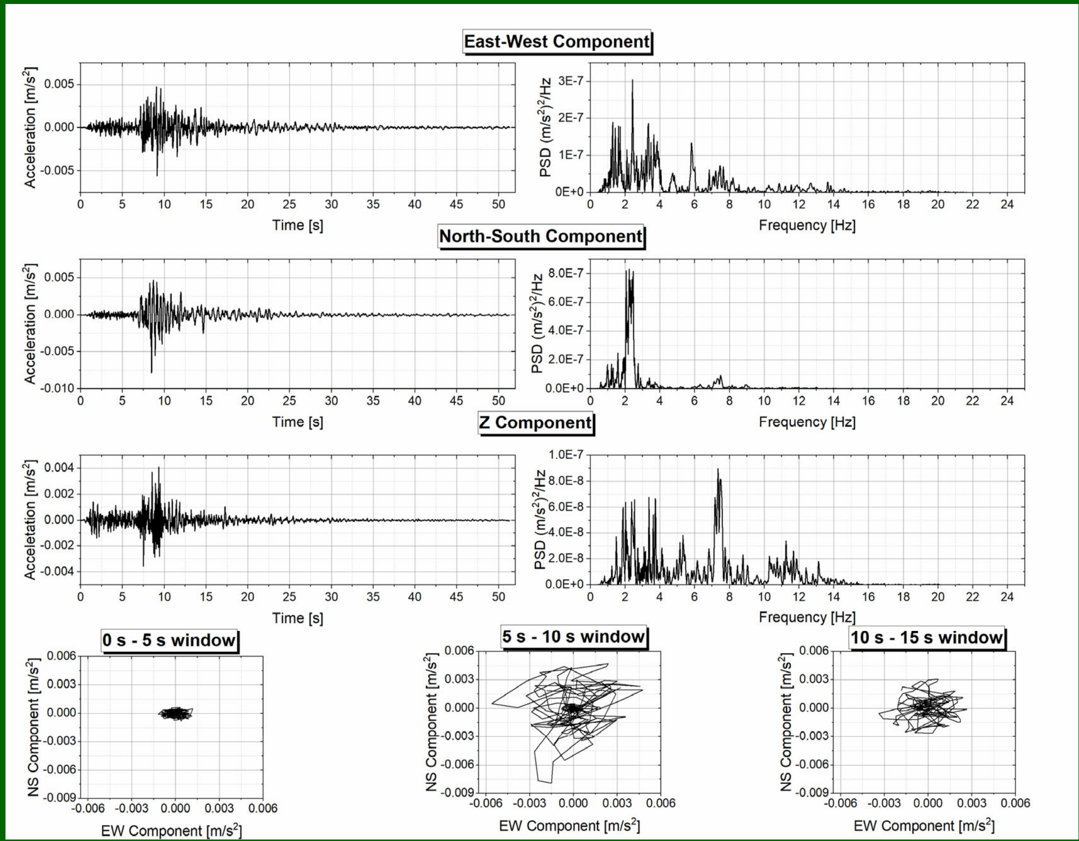
Steps of the computation of stalagmite's seismic response

- A robust, fully three dimensional Finite Element Method model was prepared and calibrated from free vibration records by Hilbert-Huang modal extraction;

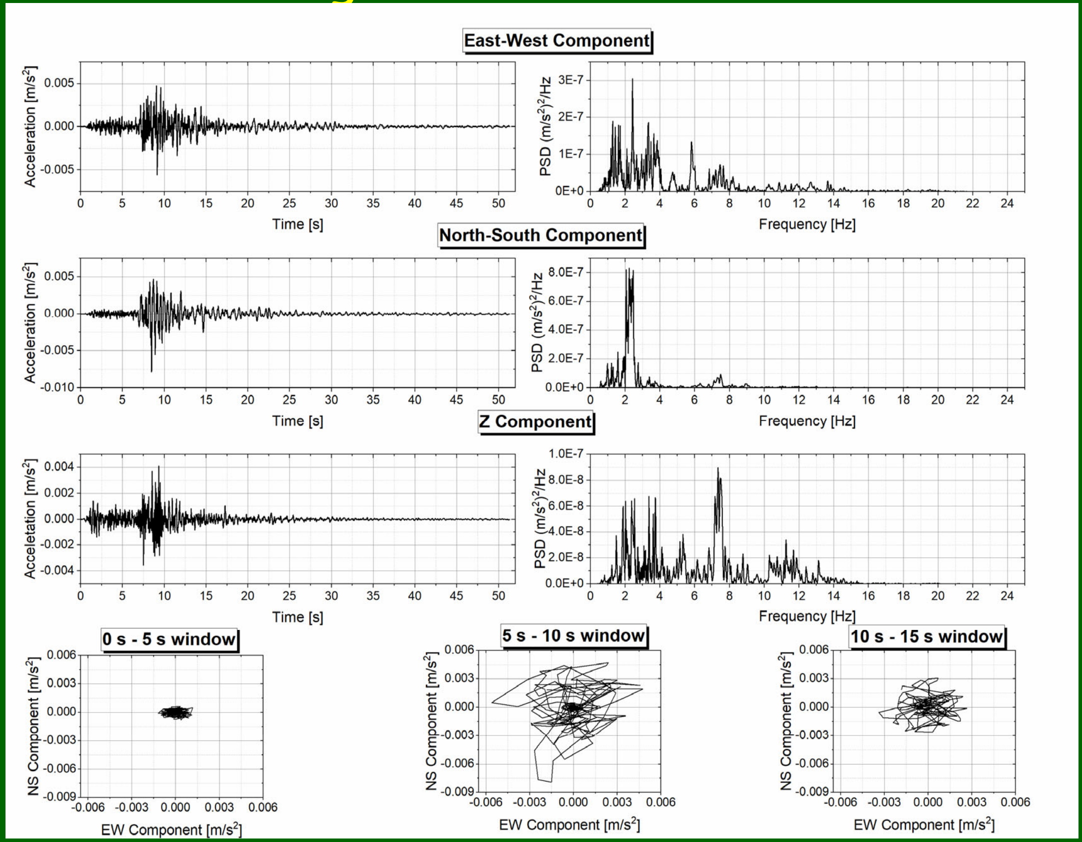
- The laser scan of the stalagmite with mm accuracy was used for constructing the FEM;

- An underground record of a moderate earthquake was then applied to excite low-intensity seismic vibrations and to study the seismic response of the speleothem using **Abaqus** program;



Steps of the computation of stalagmite's seismic response

- The investigated stalagmite is standing in a shallow cave, therefore we used a seismic ground motion recorded 60m depth under the ground;
- The earthquake generated the used underground seismic acceleration occurred at 29th January, 2011, Oroszlány, Hungary (m_L=4.5)
- The ground motion was recorded at BUD station, 60m depth below the ground surface in a dolomite hill, 50.1 km far from epicentre.



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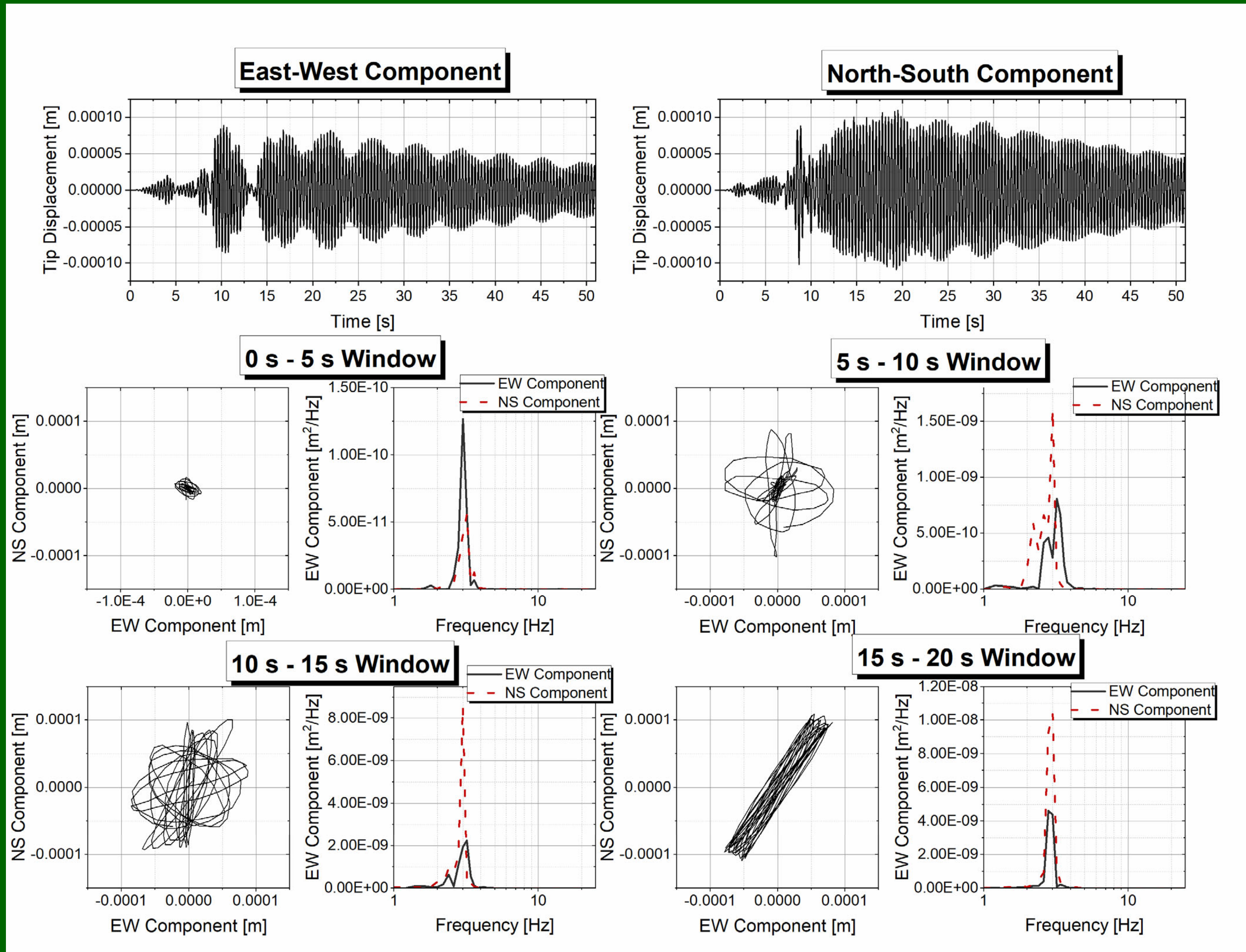
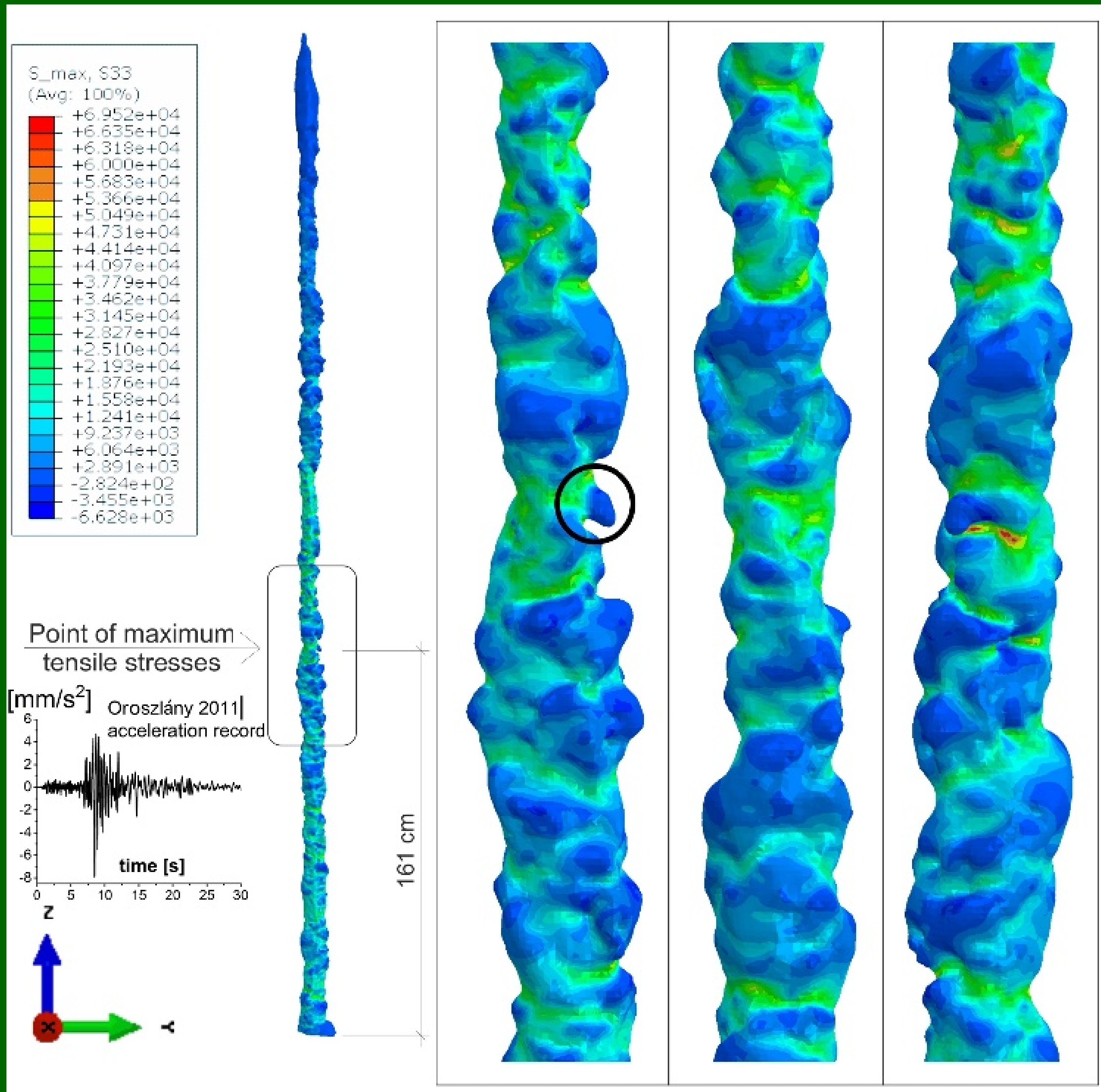
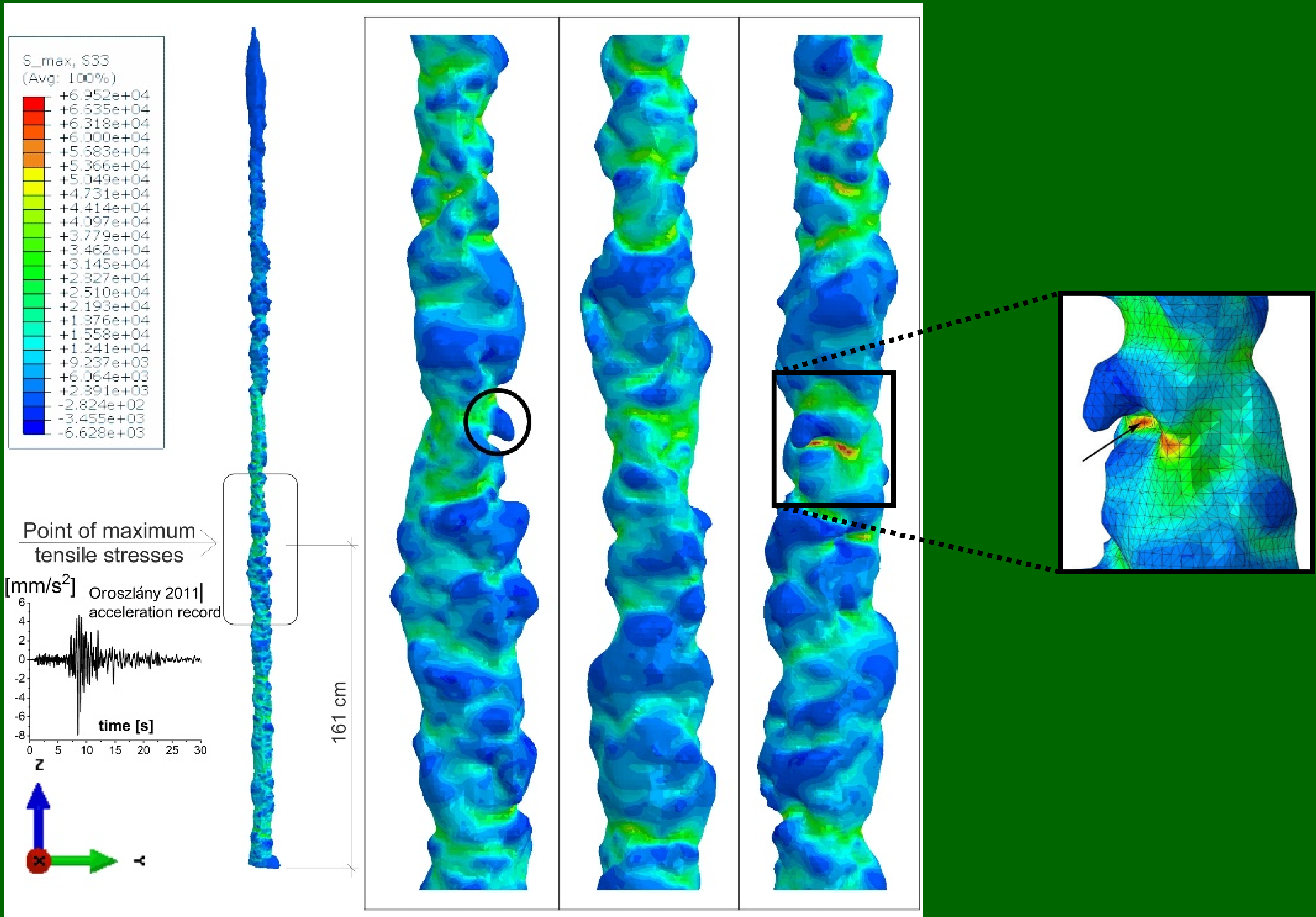
Seismic Response of the Stalagmite



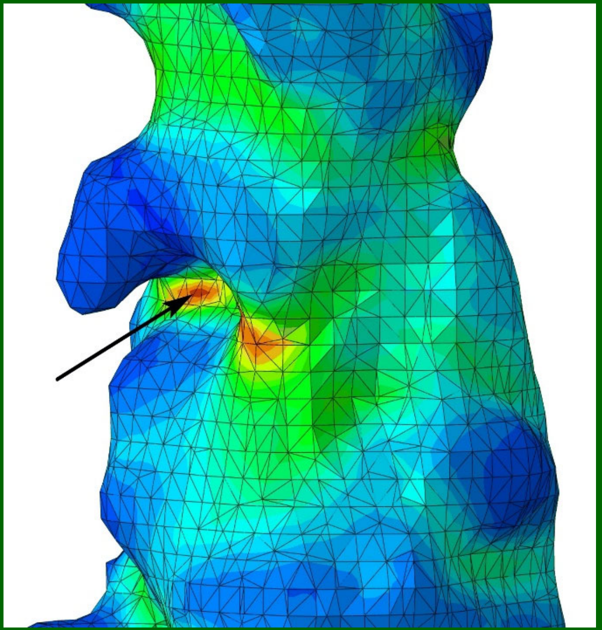
Tensile Stress Map of the Stalagmite



Tensile Stress Map of the Stalagmite



Ultimate Horizontal Peak Ground Velocity



The actual research on mechanical properties of speleothems (Gribovszki et al. 2017) makes it possible to assume a pure brittle damage behavior of this stalagmite.

It means that a linear model of stalagmite vibrations is fully appropriate in modeling its dynamics: when the tensile stress reaches ultimate value, then the stalagmite breaks.

It is concluded that the failure mode of the stalagmite is driven by flexural vibrations.

The safety margins of this stalagmite were assessed by analysing the tensile stress map from the seismic response computations. The location of the breaking point of the stalagmite is a result of a balance between the overturning bending moment and variations of horizontal cross-sections with height.

Ultimate Horizontal Peak Ground Velocity

Under the seismic excitations of the Oroszlány earthquake (record at BUD station), the maxial value of tensile stresses (0.069MPa) reached 13.7% of the breaking stresses reported from mechanical tests, as equal to 0.51 MPa.

Thus, the BUD station record of the Oroszlány earthquake (which is an underground record of a moderate EQ) could be scaled 7.3 times to the ultimate $PGV_{up\ hor}$ = 3.4 mm/s, to reach expected bending capacity of this speleothem.

This value is higher than 2.4 mm/s reported by Bottelin et al. (2020) for soda straws.

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and

Thank You for Your attention!