Constraints on Long-Term Seismic Hazard From Vulnerable Stalagmites

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SUMMARY

As for any model/theory, a probabilistic seismic hazard analysis (PSHA) model is best tested by comparing its predictions with observations that are independent, e.g. which have not been used for creating the model. Arguably, the most valuable information in the context of seismic hazard analysis is information on long-term hazard, namely maximum intensities (or magnitudes) occuring over time intervals that are at least as long as a seismic cycle. Such long-term information can in principle be gained from intact stalagmites in natural caves, and we outline the approach here. Sensitive stalagmites have survived all earthquakes that have occurred over their long time span, e.g. over thousands of years or more - depending on the age of the stalagmite. Their "survival" requires that the horizontal ground acceleration has never exceeded a certain critical value within that period. Such information is very valuable, even if it concerns only a single site, namely that of a particularly sensitive infrastructure.

Keywords: *speleology, speleoseismology, stalagmite, prehistoric earthquake, cantilever beam, seismic hazard, PGA, PSHA.*

1. Introduction

Earthquakes hit urban centers in Europe infrequently, but occasionally with disastrous effects. This raises the important issue for society, how to react to the natural hazard: potential damages are huge, and infrastructure costs for addressing these hazards are huge as well. Furthermore, seismic hazard is only one of the many hazards facing society. Societal means need to be distributed in a reasonable manner - to assure that all of these hazards (natural as well as societal) are addressed appropriately. Obtaining an unbiased view of seismic hazard (and risk) is very important therefore.

In principle, the best way to test a PSHA model is to compare its predictions with observations that are entirely independent of the procedure used to produce the PSHA models. Arguably, the most valuable information in this context should be information on long-term hazard, namely maximum intensities (or magnitudes) occuring over time intervals that are at least as long as a seismic cycle – if that exists. Such information would be very valuable, even if it concerns only a single site, namely that of a particularly sensitive infrastructure. Such a request may seem hopeless – but it is not.

Long-term information can in principle be gained from intact, vulnerable, candle-stick type stalagmites (IVS) in natural caves. These have survived all earthquakes that have occurred, over thousands of years, or longer - depending on the age of the stalagmite. Their "survival" requires that the horizontal ground acceleration has never exceeded a certain critical value within that period.

This paper is based on case studies in Austria (e.g., Gribovszki et al., 2013), which has moderate seismicity, but a well-documented history of major earthquake-induced damage, e.g., Villach in 1348 and 1690, Vienna in 1590, Leoben in 1794, and Innsbruck in 1551, 1572, and 1589. Seismic intensities have reached levels up to 10. It is clearly important to know which "worst-case" damages to expect.

We have identified sets of particularly sensitive stalagmites in the general vicinity of two major cities in Austria (Vienna and Graz). Non-destructive in-situ measurements have been performed for these and other caves in Austria and Slovakia, in order to determine the horizontal ground accelerations that would result in failure of these stalagmites. These specially-shaped intact stalagmites allow estimating the upper limit on horizontal peak ground acceleration (HPGA) generated by paleoearthquakes. Such information can help make the right strategic decisions.

2. Seismic hazard estimation by intact vulnerable stalagmites (IVS)

Several studies have considered "speleoseismology" throughout the last thirty years (Forti and Postpischl, 1984, 1988; Delaby and Quinif, 2001; Cadorin et al., 2001; Lacave et al., 2000, 2004; Kagan et al., 2005; Becker et al., 2006; Bednárik 2009; Szeidovitz et al., 2005, 2007, 2008, 2008a; Paskaleva et al., 2006, 2008; Gribovszki et al., 2008, 2013, 2013a, Shanov and Kostov, 2015).
Results of Forti and Postpischl (1984, 1988), and Delaby and Quinif (2001) have shown that examining the broken and tilted speleothems can indeed be useful for revealing historic and paleoearthquakes. Cadorin et al. (2001) have performed laboratory measurements and theoretical computations to determine the horizontal acceleration that was necessary to break the broken speleothems in the Hotton cave (Belgium). For the small speleothems in that cave, relatively strong values of acceleration were required to break them. Hence, in that case these (relatively small) speleothems appear to not be indicators of paleoearthquakes, or the earthquakes were considerably stronger than expected.
Lacave et al. (2000) have determined by in-situ measurements the natural frequencies of various types of speleothems, estimated curves describing the natural frequency as a function of the type and length of the speleothem, and computed the speleothems' viscous equivalent damping. Furthermore, Lacave et al. (2004) have constructed vulnerability curves (probability of breaking vs. peak ground acceleration [PGA] functions) for classes of differently shaped stalactites. Kagan et al. (2005) have dated broken speleothems by UTh and oxygen isotope methods in two caves in

Israel, in order to determine the age of large earthquakes affecting the territory and broke the examined speleothems.

Becker et al. (2006) have given a comprehensive critical review of speleoseismology. They describe processes other than earthquakes that can have the same or very similar effects on speleothems, and they conclude that, before a decision is made on the seismic origin of deformations and damages found in caves, alternative explanations must be taken into account as well. Bednárik (2009) has modelled numerically the displacement of stalactites excited by seismic ground motion. Shanov and Kostov (2015) have given a comprehensive study about traces of paleoseismicity and active tectonics in karst taking into account the investigation of broken and unbroken stalagmites with case studies in Bulgarian caves as well.

In the Central European region, speleothem examinations for paleoearthquake research have begun with a series of research projects named "Comprehensive investigation of recent and paleoearthquake occurred in the Carpathian Basin" between 2000-2005 in Hungary and subsequently in Bulgaria and Slovakia (Szeidovitz et al., 2005, Szeidovitz et al., 2007, Szeidovitz et al., 2008, Szeidovitz et al., 2008a, Paskaleva et al., 2006, Paskaleva et al., 2008, Gribovszki et al., 2008, Gribovszki et al., 2013, Gribovszki et al., 2013a). The results gave new and more constraining (lower) horizontal ground acceleration values for Northern Hungary. These examinations have impact on the seismic hazard assessment of the Middle-European region, as well as neighboring territories. The estimated horizontal ground acceleration results of the Bulgarian stalagmite investigation were improved by finite element numerical model calculation using SAP software as well (Paskaleva et al., 2006). In these numerical calculations the approximate shape of the stalagmite could be taken into account.

At the second part of this chapter we outline the approach how can long-term information of seismic hazard in principle be gained from intact, vulnerable, candle-stick type stalagmites (IVS) in natural caves.

Estimation of upper limit on horizontal peak ground acceleration

Values of the horizontal peak ground acceleration (HPGA) that can break IVS can be estimated by theoretical calculations based on cantilever beam theory, if we know the exact dimensions of the stalagmite and its geo-mechanical and elastic parameters. The geo-mechanical and elastic parameters of the stalagmite can be measured by using broken stalagmite samples (lying on the ground at the same hall of the cave, as the investigated stalagmite) in mechanical laboratory. The dimensions and the eigenfrequency of the stalagmite can be measured in situ in the cave.

Estimation of age, growing rate, and past shape of IVS

The next step in our method is to determine the age of the IVS at different heights. These age measurements constrain the shape of IVS during its growth period, and help to assign critical HPGA values backward into the past. If core samples can be drilled from the axis of IVS for at least two different heights the age of these core samples constrain the age and the growing rate of the IVS. Based on the age determination a simplified model of the changing shape of the investigated stalagmite going backward in the past can be constructed. If we know that the stalagmite is still growing (because it is wet) and if we assume a constant value of the growth rate (this is the determined one by using age determination results of two core samples) then we can determine the height of stalagmite backward into the past. Furthermore the results of the investigations done by Dreybrodt and Romanov (2008) have to be taken into account as well. They pointed out that candle-stick type stalagmites grow with more or less constant diameter.

Taking into account all of the above (facts and assumptions) the height of IVS going backward into the past (and the shape of the stalagmite as well, because the diameter is constant at the cross section) can be calculated as a function of the age. With the shape of IVS in the past the critical horizontal ground acceleration of the IVS can be estimated for the past (Fig. 1, 'in the cave' curve).

Attenuation of seismic waves with depth

It is known that for deeper caves, the amplification of seismic waves is weaker, or in other words, the attenuation increases (Becker et al., 2006). Therefore, it is important to know the depth of the cave, where the investigated IVS is located. If the depth of the cave is known, then the next step is to evaluate the attenuation of seismic waves by direct measurement in the cave and at the surface, or by collected data from the literature (results of measurements performed previously by others), and to multiply the critical horizontal ground acceleration (CHGA), depending on the height of the IVS, in the cave by the attenuation factor in order to get CHGA at the surface, which corresponds to the acceleration at which failure of the stalagmite would occur in the cave (see Fig. 1).

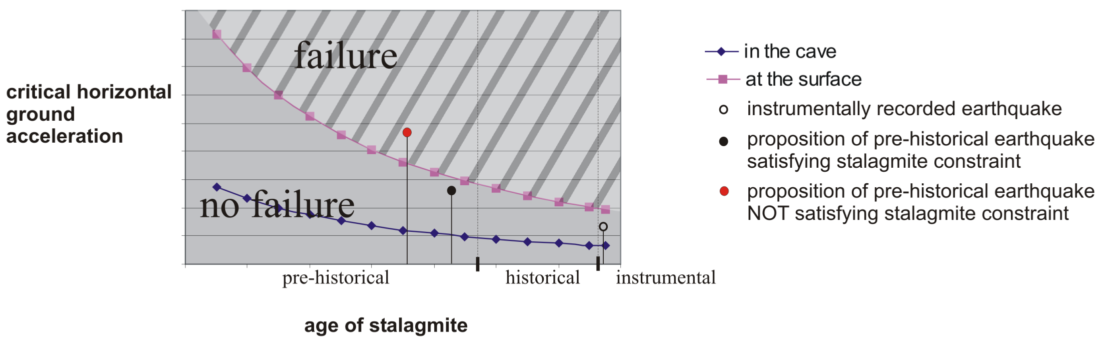

Figure 1. Illustration of the constraint on critical horizontal ground acceleration (CHGA) provided by an intact vulnerable stalagmite (IVS). As a function of stalagmite age, CHGA decreases due to increasing stalagmite height (curves), compared with measured (instrumental) and inferred (pre-historical/historical) horizontal ground accelerations.

Fig. 1 suggests how we can test propositions of pre-historical earthquakes using intact vulnerable stalagmites, and in which sense we can provide long-term upper bounds on horizontal ground acceleration. Furthermore, we can test seismic hazard models such as SHARE, and we will document this in the following, followed by a brief discussion on how this can provide constraints on seismic hazard for sites of specific interest, such as towns or critical infrastructures (dams, nuclear power plants, etc.).

3. Testing seismic hazard models (e.g., SHARE)

Seismic hazard is defined as the probable level of ground shaking associated with the recurrence of earthquakes. Basically two different types of seismic hazard models exist: probabilistic and deterministic.

The main elements of modern probabilistic seismic hazard assessment can be grouped into four main categories. The first element is the compilation of a uniform database and catalogue of seismicity for the historical, early-instrumental, and instrumental periods. The second is the creation of a master seismic source model to describe the spatial-temporal distribution of earthquakes, integrating the earthquake history with evidence from seismotectonics, paleoseismology, mapping of active faults, geodesy, and geodynamic modeling. The third is the evaluation of ground shaking as a function of earthquake size and distance, taking into account propagation effects in different tectonic and structural environments. He fourth is the computation of the probability of occurrence of ground shaking in a given time period, to produce maps of seismic hazard and related uncertainties at appropriate scales (Giardini, 1999).

In deterministic seismic hazard studies the principal objective is to determine the design ground acceleration values at different parts of the target area, which is usually a smaller area, than in probabilistic seismic hazard assessments. The knowledge of the seismic source and wave propagation process – together with the known geological structure – makes it possible to calculate by computer programs the ground motions associated with a given earthquake scenario. Using modern deterministic seismic hazard assessments the focal source, path and site effects can be all taken into account and therefore it is possible to carry out a detailed study of the propagating wave field at even large distances from the epicentre.
As a result of the modern deterministic seismic hazard computations synthetic seismograms are created and the PGA values can be determined directly from the seismograms (Panza et al., 1999).

Over the last decades, most countries in Europe have set up probabilistic seismic hazard assessment for the whole territory of the country and deterministic seismic hazard studies for smaller regions such as towns or critical infrastructures.
Four main project frameworks have aimed at improving regional seismic hazard assessment in the European-Mediterranean region, by integrating earthquake catalogues, seismic source zoning, and hazard assessment in the last fifteen years.
The Global Seismic Hazard Assessment Program (GSHAP), a UN/IDNDR demonstration project, produced the first seismic hazard map for the European-Mediterranean region as part of the Global Seismic Hazard Map (Giardini, 1999), based on the compilation and assemblage of hazard results obtained independently in different test areas and multinational programs.
The International Geological Correlation Program project n.382 Seismotectonics and seismic hazard assessment of the Mediterranean basin (SESAME) developed in 2000 the first integrated seismic source model and homogeneous hazard mapping for the Mediterranean region (Jaménez et al., 2001).
The European Seismological Commission (Working Group on Seismic Hazard Assessment) has completed the first unified seismic source model and seismic hazard mapping for Europe and the Mediterranean.
About ten years later the SHARE Project (Danciu et al., 2013) was launched. The main objective of SHARE was to provide a community-based seismic hazard model for the Euro-Mediterranean region with update mechanisms. The project aimed to establish new standards in Probabilistic Seismic Hazard Assessment (PSHA) practice by a close cooperation of leading European geologists, seismologists and engineers. The project and the resulting maps cover the whole European territory, including Turkey.
The project built a framework for integration across national borders, compiled relevant earthquake and fault data, and developed a sustainable, high-impact authoritative community-based hazard model assembled by seeking extensive expert elicitation and participation through multiple community feedback procedures.
SHARE produced among others more than sixty time-independent European Seismic Hazard Maps spanning spectral ordinates of PGA to 10 seconds and exceedance probabilities ranging from 10^{-1} to 10^{-4} yearly probability. SHARE introduced an innovative weighting scheme that reflects the importance of the input data sets considering their time horizon, thus emphasizing the geologic knowledge for products with longer time horizons and seismological data for shorter ones.

We`re using the SHARE code to extract horizontal ground accelerations for a number of different exceedence probability of earthquake, and compare them with the stalagmite-derived CHGA. This comparison is illustrated in Figure 2. In this case, the SHARE-derived values would be considerably larger than the new constraint from the stalagmites. We refer the reader to a subsequent study, where we give the specifics of this comparison for the case studies indicated above.

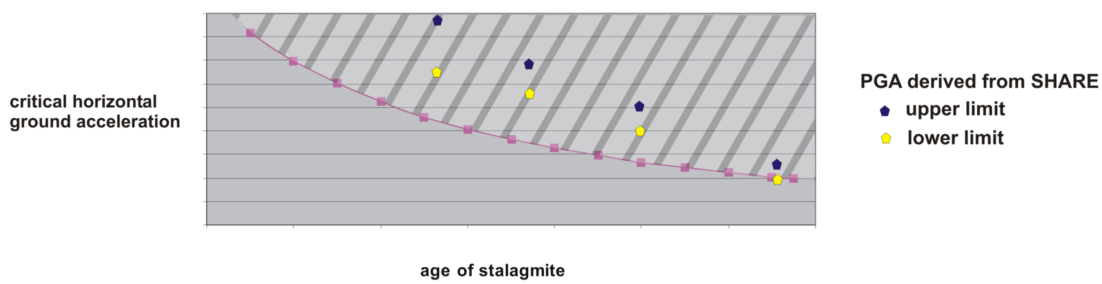

Figure 2. Comparison between stalagmite-derived critical horizontal ground acceleration and PGA derived from SHARE (illustration).

4. Local nature of the stalagmite constraint

From the stalagmite we obtain constraints on seismic hazard through model calculations. The basic concept is illustrated in Figure 3a): an intact stalagmite constrains CHGA at its location that can arise from (all) earthquakes in the area, which is just enough to break the stalagmite. The main purpose of this model calculation is to redistribute that CHGA onto potential sites of earthquakes. Figure 3b) illustrates this redistribution, showing that the constraint acts more strongly on closer sites than more distant ones. The redistribution requires (at least approximate) knowledge of propagation properties of seismic waves, especially their attenuation with distance.

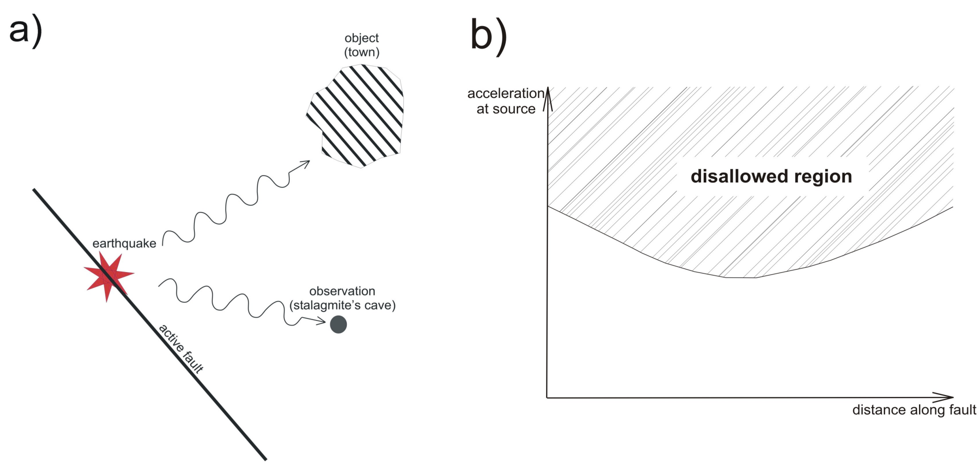

Figure 3. a) Sketch of the three-site seismic hazard model calculation (seismic waves propagate from an earthquake source to the object and the observation cave); b) type of constraint offered by the intactness of a stalagmite on maximum acceleration at the position of potential earthquake sources.

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