The use of speleothems to better constrain long return period seismic hazard in Lebanon

C. Lacave
Résonance Ingénieurs-Conseils SA, Carouge (GE), Switzerland

B. Sadier & J.-J. Delannoy
Laboratoire EDYTEM, Le Bourget-du-Lac, France

C. Nehme
St Joseph University, Beirut, Lebanon - Laboratoire EDYTEM, Le Bourget-du-Lac, France

J.-J. Egozcue
U. Politécnica de Cataluña, Barcelona, Spain

SUMMARY:
In the framework of the LIBRIS project (Contribution to seismic risk assessment in Lebanon), a work package is devoted to the use of broken or unbroken speleothems (stalagmites and stalactites) to better characterize the local seismic hazard. This kind of study is particularly interesting in the long return period range, where historical information is far from being sufficient. The proposed approach is based on a previous study by Lacave et al. (2004). Two pilot caves, located north of Beirut, along or close to a major fault, were first selected. Then, in situ measurements of speleothems were done using a 3D laser scan. The data were processed to obtain a detailed sampling of the broken and unbroken speleothem population (number, precise shape). These data are finally used to compute, in a statistical approach, the probability of exceeding, or non exceeding, of a certain level of seismic acceleration in the study area.

Keywords: speleothems, maximum acceleration, seismic hazard, long return period

1. INTRODUCTION

In the framework of the LIBRIS project (Contribution to the study of seismic risk in Lebanon), a work-package is devoted to the use of information derived from the study of broken or unbroken speleothems (stalactites and stalagmites), in order to better characterize the seismic hazard in a given region. This kind of study potentially contributes to the determination of long return period hazard, not covered by historical seismicity. A critical review of many studies conducted in the field of speleo-seismicity can be found in Becker et al. (2006).

Another similar field of research is also investigated by Anderson et al. (2011), with the same goal, using precariously balanced rocks or other fragile geological features. Indeed, probabilistic seismic hazard analysis (PSHA) is not very reliable at low probabilities where no instrumental verification is possible. Anderson et al. (2011) conclude that to gain confidence in PSHA it is important to use fragile geological features (precariously balanced rocks or speleothems, for example) to test hazard curves at low probabilities, whenever data are available.

2. METHODOLOGY

The proposed approach is based on a previous study by Lacave et al. (2004). The mechanical behaviour of speleothems was studied by means of static bending tests performed on pieces of broken stalactites, giving indications of their mean bending resistance as well as on its variability. This study made it possible to determine fragility curves for different classes of speleothems, by means of Monte Carlo type simulations, accounting for dynamic amplification and bending resistance heterogeneity, in each speleothem. Finally, an original statistical approach, valid for incomplete and imprecise data, was developed. This approach allowed to estimate the probability that at least one relatively strong earthquake has occurred in the past.

A first field trip was conducted in February / March 2010, allowing the choice of two pilot caves. A second field trip, conducted in October 2010, was devoted to in situ 3D laser measurements. The processing of the acquired data makes it possible to precisely sample the broken and unbroken speleothems populations (number and precise shape), in both pilot caves. These data constitutes the basis for the statistical computation of the probability of having reached, or not attained, a certain level of seismic acceleration in the studied region.

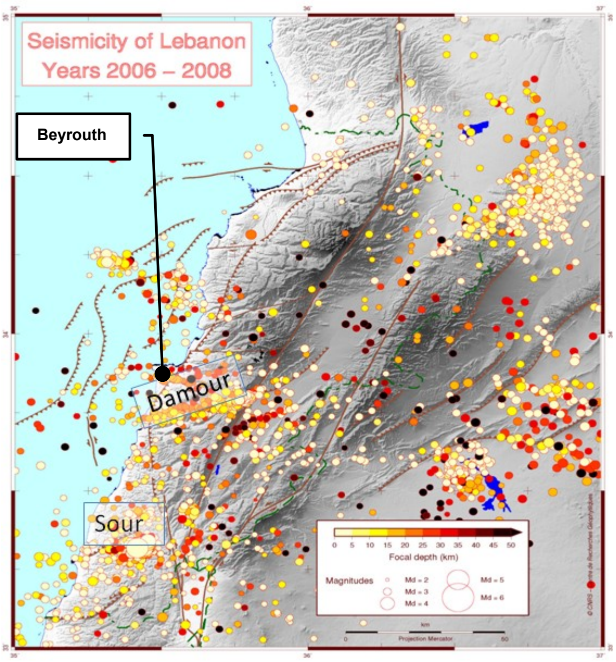

Figure 1. Lebanon seismicity between 2006 and 2008.

3. PILOT CAVES

Criteria for the choice of the two pilot caves were as follows:

- Location in a seismic area (after the historical and instrumental seismic maps for Lebanon, as the one shown on Figure 1, for example).
- Caves containing rather slender speleothems (long and thin). There should be an important number of speleothems, if possible broken and unbroken ones. The use of soda-straws is not possible as it is impossible to distinguish a broken from an unbroken soda-straw.
- If broken speleothems are present, one must try and estimate their original size (by means of broken pieces on the floor, shape indices, etc.).
- Study areas with speleothem populations should be at shallow depth, so that the ground acceleration can be considered as approximately being the same as the surface rock acceleration.

Based on these criteria, colleagues from the ALES (Lebanese association for speleological studies) and St Joseph University (Beirut, Lebanon) prepared a list of potentially interesting caves for the project. These caves were visited during the first field trip, in order to choose interesting pilot caves.

It must be noted here that it is very important, in all visited cave, to account for many different elements that may cause speleothems rupture, other than earthquakes. Examples of these can be:

- quarry blasting,
- bombardments,

– human activity (pilfering, vandalism, etc.).

During the cave visits, these potential human causes of braking were seriously considered, in order to select as pilot caves the ones that present the least potential of human origin of breaking. The two selected pilot caves are the caves of Jeita (Nahr El Kalb) and Kanaan (Antelias), both located near the coast, North of Beirut, on - or in the prolongation of - a major fault, as shown on the schematic map on Figure 2. The characteristics of both caves are described hereafter.

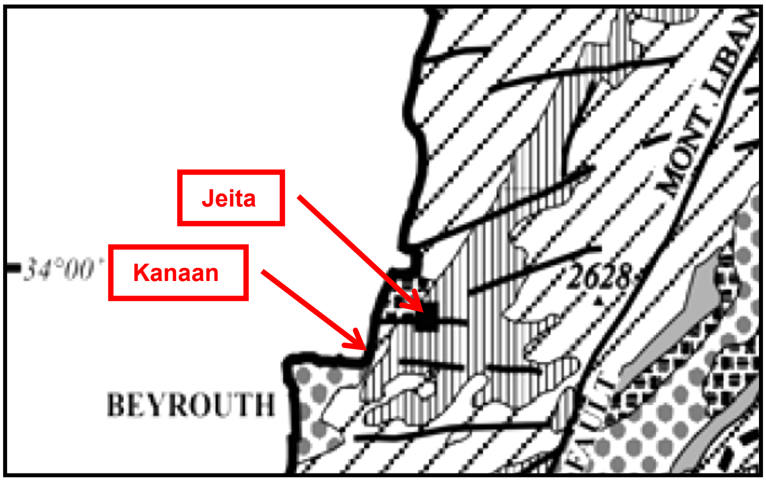

Figure 2. Location of the two selected pilot caves, both situated on – or in the prolongation of – a major fault (from the simplified geologic map of Lebanon, Dubertret, 1955).

3.1. Jeita cave

Jeita cave is one of the major caves in Lebanon, due to its development (more that 10 km) as well as to the vastness of its volumes and the richness of its speleothems population. It is located on the hillside of the narrow Nahr El Kalb valley, North of Beirut, along a major fault (Figure 2).

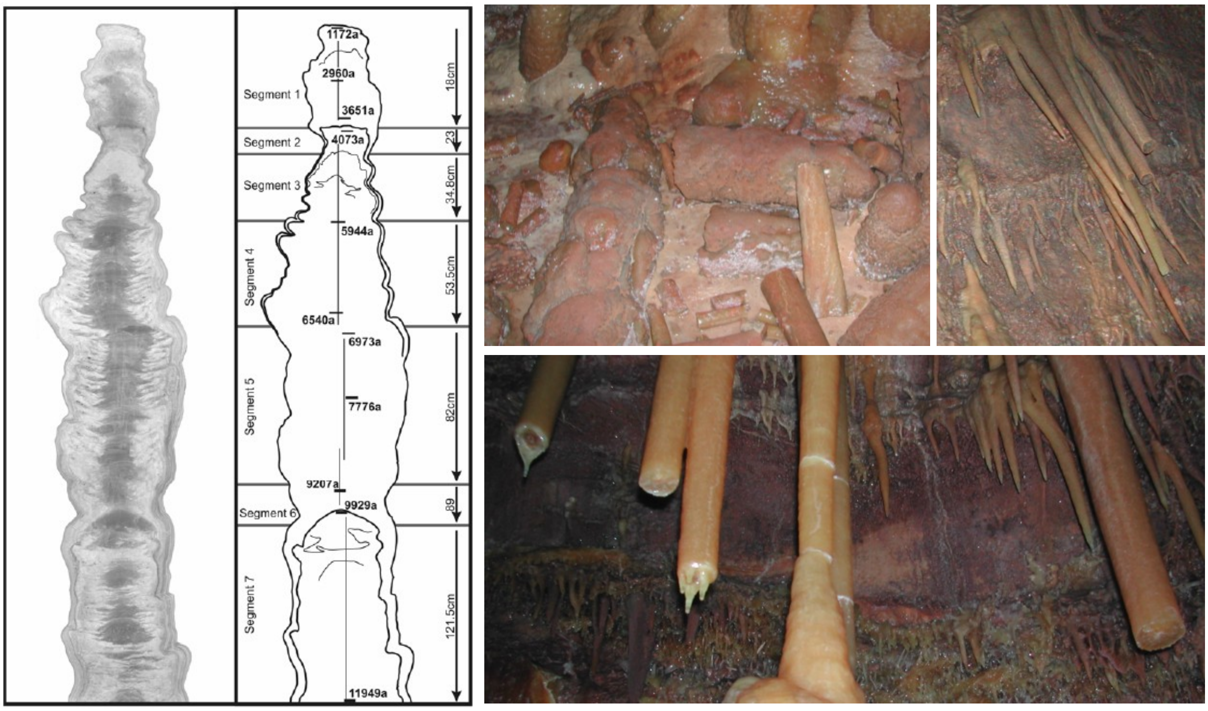

Figure 3. Left: results of the dating of a stalagmite in Jeita cave, conducted by Nader et al. (2007). A clear rupture can be observed at about -4000 years. Right: broken speleothems in the cave of Kanaan. On the bottom picture, breakings along the two middle columns could be due to drawing off phenomena at their basement.

This cave constitutes an exceptional paleo-environmental recording, as evidenced by the dating conducted by Nader et al. (2007), on a stalagmite sampled in the cave (Figure 3), with ages of the beginning of the speleothem formation as about 12000 years before present days. During the first field trip, part of Jeita cave was visited, especially a lateral gallery located above the touristic area, as well as another lateral gallery, located further than the touristic section. Many broken speleothems (especially long stalactites) were observed in the gallery located above the touristic section. This gallery was then selected as investigation site for the following of the project.

3.2. Kanaan cave

The cave of Kanaan is located in the quarry of Antelias; its entrance is formed by a rather vast porch opened in the quarry wall. Kanaan is characterized by a rich speleothem population, associated with many interesting indices allowing the reconstitution of the karstic history and evolution of the cave (Nehme et al., 2009).

Concerning the LIBRIS project, the cave of Kanaan constitutes a very interesting study area thanks to its important speleothem population, of large dimensions, broken as well as unbroken (Figure 3). Interesting is to note that the broken stalactites shown on Figure 3 are broken since several hundreds of years, as shown by the re-growths at their extremities. This makes it possible to consider that the breaking occurred prior to the quarry exploitation.

4. SPELEOTHEM POPULATION MEASUREMENTS

4.1. In situ measurements

Data acquisition was extracted from high resolution digital terrain models recorded by 3D laser sampling. The field trip conducted in October 2010 made it possible to acquire in situ data by means of a Leica HDS 6000 Lidar (Figure 4), on a dome of 360° by 310°.

Figure 4. Setting and details of the high speed and high resolution 3D laser scanner, used for the sampling of the speleothems populations.

This equipment is able to measure from up to a distance of 70 m and register about 500000 points per second with a maximum resolution of 1 mm at a distance of 10 m, which corresponds to an angular step of 127 μm between each measure. However, the precision in the positioning of each point is given to be 2 mm, in x, y and z directions, up to a distance of 25 m. Details on the validation of this in situ measurement technique is given in the publication by Sadier et al. (2011).

In the cave of Jeita, for example, 49 scanner locations were necessary to cover the whole study area, with a point density chosen as a function of the distance between the scanner and the ceilings where the stalactites are located. A heavy data processing is then applied in order to restore and combine the measurement scenes between them, with a precision of 3 mm. Horizontality and orientation were obtained by geo-referencing with an electronic compass and a compensator integrated in the scanner.

4.2. Data processing

Details on the restoration procedure used in order to be able to proceed to the speleothems measurements are given in the publication by Sadier et al. (2011). After this heavy processing, in the case of the cave of Jeita, 37 scenes were selected, on which the total number of measured points was kept. The represents scenes constituted of 75 to 175 millions of points. Finally, the global cloud of points is made of more than 3.3 milliards of points. In becomes then possible to conduct direct measurements on the pictures (Figure 5), as one easily navigates through the 3D numerical model.

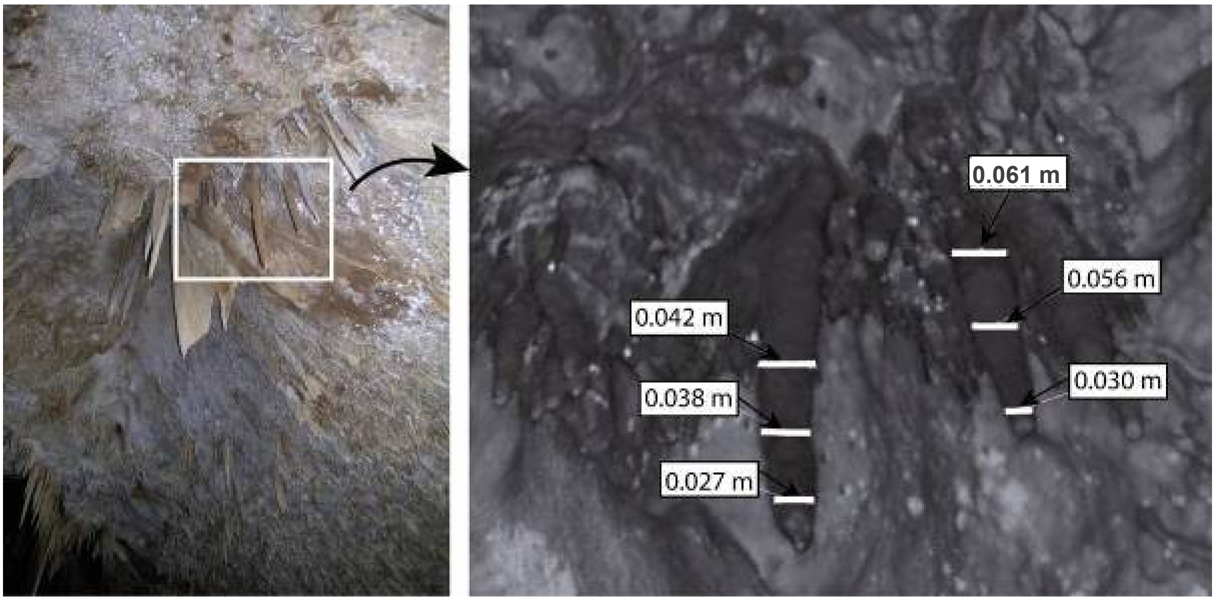

Figure 5. Extract of a solid picture from the 3D numerical model on which one can directly measure the speleothems size (right). The left picture is a photo of the same area directly taken on the field with a camera (from Sadier et al., 2011).

5. VULNERABILITY ANALYSIS

A study previously conducted by Lacave et al. (2004) allowed developing a model of speleothem behaviour under seismic solicitation. This approach also included the account for uncertainties linked to the shape of the speleothem, to the heterogeneity of its internal structure, to possible dynamic amplification effects, etc. The conducted modelling made it possible to establish fragility curves for speleothems (Figure 6), associated to four vulnerability classes ranging from "highly vulnerable" to "not vulnerable", respectively. A stalactite, about 80 cm long, with a diameter ranging between 2 and 2.5 cm belongs to the vulnerability class 1, whereas a stalactite of 50 cm in length and with a diameter of 1 to 2 cm belongs to the vulnerability class 2, for example. Fragility curves shown on Figure 6 show that, for example, with an acceleration of 3 m/s^2, there is about 30 % probability to break a stalactite of class 2, whereas there is about 90 % probability to break a stalactite of class 1.

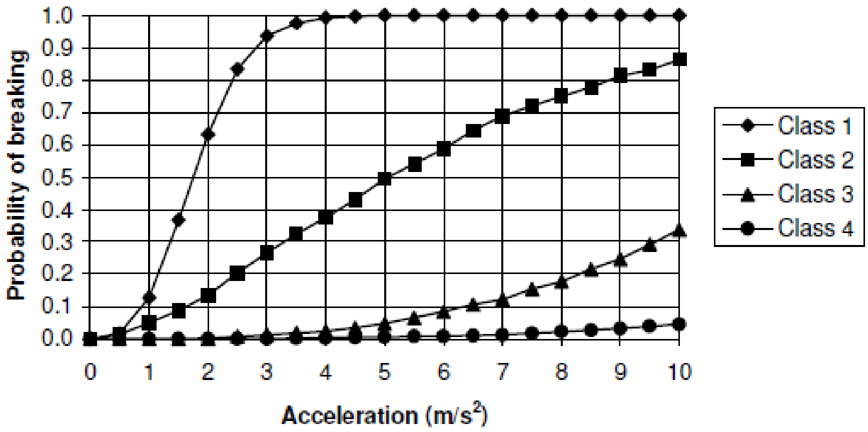

Figure 6. Fragility curves (probability of breaking as a function of acceleration) for four stalactite classes (from Lacave et al., 2004).

After the speleothem's geometry has been measured precisely, it is possible to proceed to a classification of the whole speleothems population, broken and unbroken, into the four vulnerability classes. Then, an original statistical approach, valid for incomplete and imprecise data, developed by J.-J. Egozcue (Lacave et al., 2004), is applied to the whole dataset. This procedure accounts for the uncertainty of the classification of each speleothem in one or another vulnerability class. It also accounts for the uncertainty on the fact that the speleothem has, or not, been actually broken, and if yes, potentially by a non seismic cause. Finally, this approach allows an estimation of the probability that a certain level of acceleration was reached, or not attained, during a certain period of time, in the studied region. This result, for several caves, combined with the results of other paleo-seismicity studies in the considered region, makes it possible to better determine long return period seismic hazard in Lebanon.

6. CONCLUSION

In the framework of the LIBRIS project, two pilot caves were selected north of Beirut, located on, or in line with, a major fault. A 3D laser scanning field campaign made it possible to measure all speleothems in a selected area in both caves. The processing of the acquired data allows a detailed sampling of the broken and unbroken speleothem population (number and precise shape measurements), in both caves. These data are the basis of the statistical approach to compute the probability of having reached or not exceeded a certain level of acceleration in the considered region. This will finally contribute to a better determination of long return seismic hazard in Lebanon.

AKCNOWLEDGEMENT
The LIBRIS project is financed by the ANR (French national agency for research) and the IRD (French institute of research for development). All the work conducted here would not have been possible without the active collaboration of the members of the St Joseph University, Beirut, Lebanon and of the ALES (Lebanese association for speleological studies); we would like to warmly acknowledge all of them here.

REFERENCES

Anderson J.G., J.N. Brune, M. Purvance, G. Biasi and R. Anooshehpoor (2011). Benefits of the use of precariously balanced rocks and other fragile geological features for testing the predictions of probabilistic seismic hazard analysis. *11th International Conference on Applications of Statistics and Probability in Civil Engineering.* Zürich, Switzerland.

Becker A., C.A. Davenport, U. Eichenberger, E. Gilli, P.-Y. Jeannin and C. Lacave (2006). Speleoseismology: A

critical perspective. *Journal of Seismology*, **vol. 10**, pp. 371–388. DOI 10.1007/s10950-006-9017-z.
Dubertret L. (1955). Carte géologique du Liban au 1/200000 avec notice explicative. République Libanaise, Ministère des Travaux Publics, Beyrouth, 74 p.
Lacave C., M. G. Koller and J. J. Egozcue (2004). What can be concluded about seismic history from broken and unbroken speleothems ? *Journal of Earthquake Engineering*, **Vol. 8, No. 3**, pp. 431-455.
Nader F. H., S. Verheyden, H. Cheng and R. Swennen (2007). Etude pétrographique et géochimique d'une stalagmite de la grotte de Jeita (Liban). *Lebanese Science Journal*, **Vol. 8, No. 2**, pp. 45-58.
Nehme C., Jabbour-Gédéon B., Gérard P.-C., Sadier B., Delannoy J.-J. (2009). Reconstitution spéléogénique de la grotte de Kanaan (Antélias, Liban) : contribution à la morphogenèse du nahr Antelias. *Karstologia*, **54**, pp. 21-36.
Sadier B., C. Lacave, J.- J. Delannoy et S. Jaillet (2011). Relevés lasergrammétriques et calibration sur calcite de morphologies externes de spéléothèmes pour une étude paléo-sismologique du Liban. *Cahier de géographie et de géologie - collection EDYTEM,* **n°12**, Université de Savoie, (Images et modèles 3D en milieu naturels), pp. 79-98.