A High-Resolution Seismological Experiment to Evaluate and Monitor the Seismic Response of the Saint-Guérin Arch Dam, French Alps

Eleni Koufoudi, Emmanuel Chaljub, Isabelle Douste-bacqué, Sandrine Roussel, Pierre-Yves Bard, Éric Larose, Frédéric Dufour, Nicolas Humbert, Laurent Baillet

A High-Resolution Seismological Experiment to Evaluate and Monitor the Seismic Response of the Saint-Guérin Arch Dam, French Alps

by Eleni Koufoudi, Emmanuel Chaljub, Isabelle Douste-Bacqué, Sandrine Roussel, Pierre-Yves Bard, Eric Larose, Frédéric Dufour, Nicolas Hum-bert, and Laurent Baillet

ABSTRACT

A dense seismological array using up to 19 high-sensitivity intermediate period sensors was deployed during 1 yr on and around the Saint-Guérin arch dam in the Alps to (1) quantify the spatial variability of earthquake motions at the base of the dam and (2) monitor the changes in the dynamic response of the dam and its surroundings caused by environmental forcings. The Saint-Guérin experiment is the first high-resolution seismological monitoring campaign performed on a French arch dam with open data access to the seismological and engineering community from June 2019.

INTRODUCTION: EXPERIMENT MOTIVATION

In situ measurements of the seismic response of dams are useful both to monitor their dynamic properties and to help calibrate numerical models for further design applications. Here, we present a 1-yr-long experimental campaign that targeted the Saint-Guérin dam, a double-curvature arch concrete dam located in the Alps (see Fig. 1). The motivation for the experimentation was twofold. First, it obtained dense earthquake recordings at the dam–rock interface to quantify the spatial variability of seismic motions at the foot of a typical arch dam and further help the engineering community to define realistic input motions for design applications. Second, it monitored the changes in the dynamic response of the dam and its immediate surroundings caused by environmental forcings such as variations of external temperature or of water level in the dam's reservoir (see e.g., Larose *et al.*, 2015, for a review of environmental seismology).

The experiment was conducted by a joint group involving researchers in seismology and structural dynamics from the ISTerre and 3SR labs of the Université Grenoble Alpes and engineers from the hydraulic engineering center of Électricité De France (EDF), the historical French power supplier, in Chambéry. The Saint-Guérin dam was first instrumented with 19 intermediate period seismometers from June to December 2015, then with 13 sensors from January to June 2016. The array provided continuous recordings of ambient seismic noise and high-quality recordings of 55 local events with magnitude comprised between 1.5 and 4 in the first period of the experiment and of 30 more events with magnitude above 2 in the second period. Some information regarding the Saint-Guérin experimental campaign was already presented in Koufoudi *et al.* (2017). However, the latter article is focused on the variability (in phase and amplitude) of the ground motions at the foot of the dam; thus, the information provided therein is incomplete and adapted to its needs. Herein, we provide a complete presentation of the experimentation and its broad research applications, including the monitoring of the dynamic response of the dam with ambient noise.

Compared to previous instrumentation of dams (see e.g., Yang *et al.*, 2017, and references therein), the Saint-Guérin seismological array provides a unique high-resolution dataset of weak ground motions, which will be opened to the seismological and engineering community in June 2019.

EXPERIMENT DESIGN

The design of the experiment is shown in Figure 2. A total of 19 stations from the Réseau Sismologique et Géodésique Français (RESIF)-SISMOB French national pool of instruments were deployed in June 2015 by a joint team between the ISTerre and 3SR labs and the EDF-Centre d'Ingénierie Hydraulique (CIH) research unit. Twelve stations were installed directly on the dam structure, either on the crest or along the dam–rock interface. Five more stations were installed in the immediate vicinity of the dam to serve as reference (either for amplification or for spatial variability studies), and two stations were installed along the banks of the dam's reservoir to monitor possible changes related to variations of temperature and water level. Because of the difficulty to access the foot of the dam in winter conditions, the six stations sitting along the left (SG06, SG07, and SG08) and right (SG10, SG11, and SG12) banks of the dam–rock interface (respectively labeled as L and R in Fig. 2) were dismantled in December 2015, after

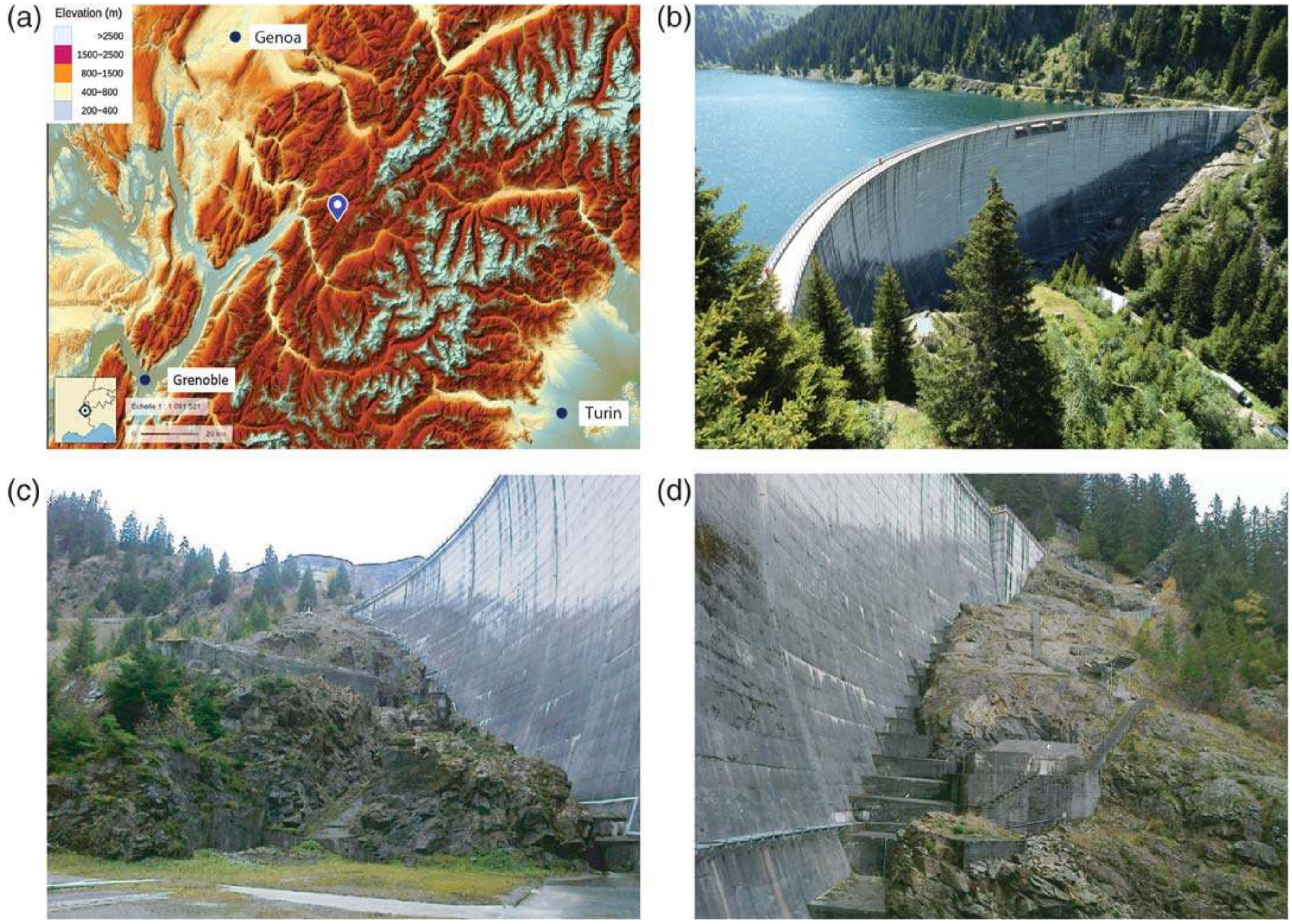

Figure 1. (a) Location of the Saint-Guérin dam (blue marker), (b) wide view of the double curved arch dam taken from the northeast. (c, d) Detailed views of the dam–rock interface along the right and left banks of the reservoir, respectively.

six months of operation. The distances between stations are indicated in Table 1.

The details of the deployed stations are shown in Figure 3. All stations were equipped with 24-bit Nanometrics Taurus digitizers operating continuously at 200 samples per second with Global Positioning System timing and three-component intermediate period seismometers. We used Güralp CMG40T sensors with flat velocity response from 50 to 0.033 Hz (30 s) and sensitivity 800 V/m/s, except for the three crest stations SG02, SG03, and SG04, for which Lennartz-3D-5s sensors with flat velocity response from 50 to 0.2 Hz (5 s) and sensitivity 400 V/m/s were installed, due to space limitations. The full scale of the digitizers was set to ± 20 and ± 8 V when connected to the CMG40T and Lennartz-3D-5s sensors, respectively.

DATA QUALITY AND AVAILABILITY

The seismic stations of the Saint-Guérin experiment operated continuously (all 19 stations from June to December 2015, then only 13 stations from January to June 2016), recording seismic noise as well as local, regional, and teleseismic events. The latter (e.g., the 16 September 2015 **M** 8.3 Chile event) were used to measure time synchronization and sensor orientation and to calibrate the amplitude of the digitized signals. During the first six months of the experiment, when all 19 sensors were deployed, a total of 55 local seismic events with local magnitude above 1.5 were recorded by the network (see table 2 in Koufoudi *et al.*, 2017, for a full description). The location and magnitude information of the events were provided by the French national seismic monitoring network RÉNASS (see Data and Resources). They are shown in Figure 4, together with the distribution of available recordings per station and per event. About 6% of the total possible number of recordings (55×19) for the first six months was missing due to station malfunctions, mainly caused by power outages. In addition, an average of 25% per station was further discarded if they did not have a signal-to-noise ratio above 3 in the [1–20] Hz frequency range. For the stations on the crest (SG02, SG03, and SG04), the rejection percentage reached 75% because of the higher level of noise due both to a poorer isolation of the sensors from environmental forcings, in particular the wind, and to the constant excitation of the dam

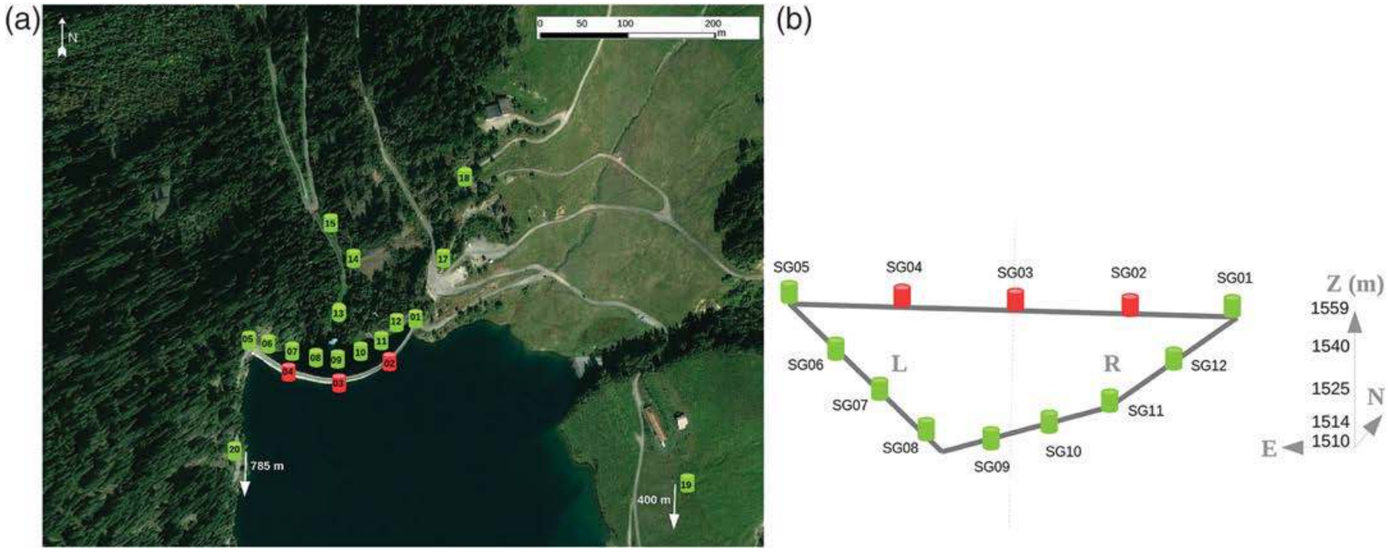

Figure 2. (a) Sketch of the deployment of the 19 stations of the Saint-Guérin (SG) experiment. The first 12 stations are installed on the dam, either on the crest (SG01–SG05) or along the dam–rock interface (SG06–SG12). The L and R letters indicate the left and right banks, respectively. The remaining stations are installed along a private road giving downstream access to the dam (SG13–SG15), at rock sites on the right bank of the dam (SG17 and SG18), and along the two banks of the reservoir (SG19 and SG20). The different colors indicate the type of sensor used: CMG40T (green) or Lennartz-3D-5s (red). (b) Zoom in the station configuration on the dam's body including the elevation level. This figure is a modified version of figure 1 from Koufoudi et al. (2017).

eigenvibrations in the ambient noise for frequencies above 4 Hz. For the latest part of the experiment, in 2016, the recordings of 30 more events with local magnitude above 2 are available.

Following the policy of the RESIF-SISMOB infrastructure, the Saint-Guérin dataset will be accessible through the RESIF website in June 2019, 3 yrs after the network was removed (see Data and Resources).

Table 1
Station Separation (Beeline) Distances (m)

	SG01	SG02	SG03	SG04	SG05	SG06	SG07	SG08	SG09	SG10	SG11	SG12	SG13	SG14	SG15	SG17	SG18	SG19	SG20
SG01	0																		
SG02	57	0																	
SG03	111	58	0																
SG04	159	112	58	0															
SG05	202	168	123	70	0														
SG06	185	146	99	46	35	0													
SG07	172	131	83	40	60	25	0												
SG08	161	118	73	46	82	48	23	0											
SG09	119	75	49	76	132	100	77	57	0										
SG10	95	54	54	96	151	122	101	81	28	0									
SG11	68	36	65	114	166	140	122	105	55	27	0								
SG12	31	33	86	136	185	164	149	135	90	64	37	0							
SG13	107	95	87	95	117	95	80	66	59	55	60	78	0						
SG14	97	101	106	114	123	115	103	95	114	82	61	79	55	0					
SG15	147	159	157	148	127	141	136	142	174	151	124	136	115	60	0				
SG17	72	122	173	205	225	225	212	201	166	151	107	107	148	119	135	0			
SG18	178	226	271	296	301	311	302	296	246	255	211	211	244	208	189	107	0		
SG19	516	489	502	544	608	581	572	549	608	506	526	512	560	584	647	574	655	0	
SG20	938	886	847	847	885	865	867	860	939	878	913	905	914	947	995	1006	1103	640	0

Modified after Koufoudi *et al.* (2017).

Figure 3. Station details. (a) Final installation of a station along the dam–rock interface. (b) The gray plastic cylinder sealed within the concrete slab contains the CMG40T sensor surrounded by a thermal isolation wool, and (c) the blue plastic device contains the Nanometrics Taurus digitizer and its cables. (d) The Lennartz-3D-5s sensors installed on the crest of the dam use smaller plastic cylinders and no thermal isolation. (e) A Global Positioning System (GPS) receiver is added to each station for time synchonization.

FIRST OBSERVATIONS AND RESULTS

The continuous recordings of the Saint-Guérin experiment can be used to investigate the linear elastic response of a simple concrete arch dam to earthquakes and seismic ambient noise and to study the details of the seismic wavefield at the base of the dam. We provide examples of two types of preliminary analyses using the recordings of ambient noise and local earthquakes.

First, we show in Figure 5 the time evolution of the lowest eigenfrequencies of the dam (between 3 and 5 Hz) measured in the ambient noise during the 1-yr-long Saint-Guérin experiment. The colors represent the variations of the normalized daily average of power spectral density computed for the north–south component of ground velocity measured at the central station (SG03, see Fig. 2), along the dam's crest. The maximum values (indicated by the red color) correspond to resonance frequencies of the dam along the direction roughly perpendicular to the dam–water interface. Those frequencies are quite stable, around 3.9 Hz, during the first four months of the deployment. From November onward, they vary rapidly and significantly between 3.9 and 4.7 Hz. The first period corresponds to a stable and maximum water level in the reservoir, whereas the second is composed of a production phase, during which the reservoir is progressively emptied until mid-February to generate electricity, followed by a refilling of the reservoir. The spectra at 3.85 and 4.1 Hz are excited at about the same level between November 2015 and January 2016. Based on a finite-element modal analysis of a simplified model of the dam with full water level (see Fig. 6), we attribute the lower of the two resonance frequencies to an antisymmetric (relative to the middle of the dam's crest) mode and the close by higher frequency to a symmetric mode which appears to be excited when the water level decreases. Also the first large increase of the dam's resonance frequency, around mid-January, coincides with the first freezing episode of the winter period (several days during which the temperature does not exceed zero) illustrating the possibly strong control of temperature on the dam's mechanical response when the water is at its lowest level.

As a second example, the phase variability of the seismic motions is estimated by computing the lagged coherency (see e.g., Zerva, 2009, p. 42) between different couples of stations along the dam–rock interface and away from the dam in the free field. Example waveforms (velocity time histories of the most energetic north–south component) along with the chosen *S*-wave window used for coherency measurements are included in figure 7 of Koufoudi *et al.* (2017). The waveforms allow to appreciate the phase and amplitude variability across the Saint-Guérin network. In Figure 7, we show the median values (over all available earthquake recordings) of the lagged coherency measured on the north–south component for

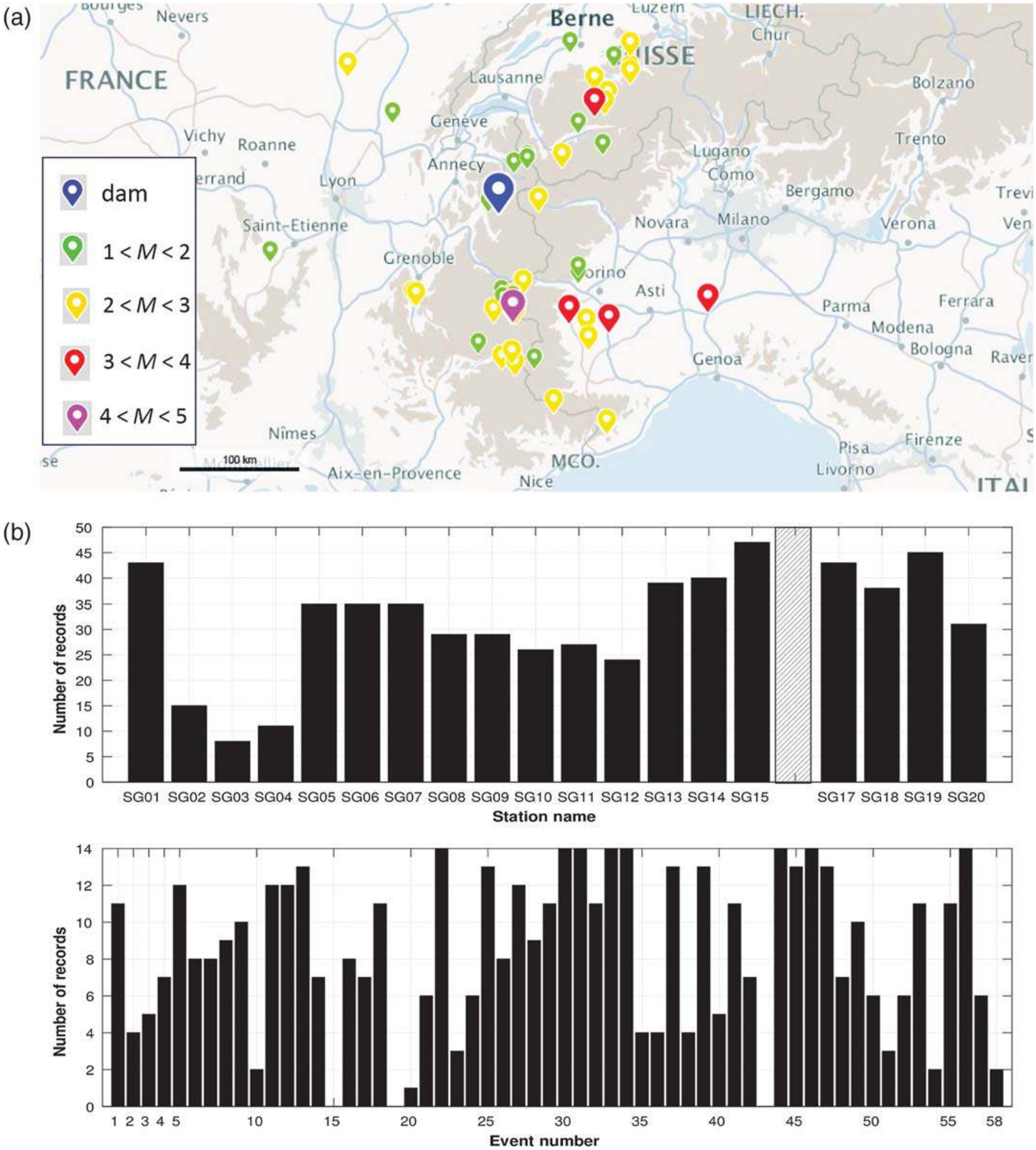

Figure 4. (a) Location of the 55 seismic events recorded by the 19 stations of the Saint-Guérin network during six months between June and December 2015. Green symbols are used for the 23 events with local magnitude M∈[1 – 2], yellow for the 28 events with M∈[2 – 3], red for the 4 events with M∈[3 – 4], and purple for the one event with M>4. (b,c) Total number of available recordings per station and per event, respectively. Station SG16 was not installed and thus appears as a bar with diagonal lines in (b).

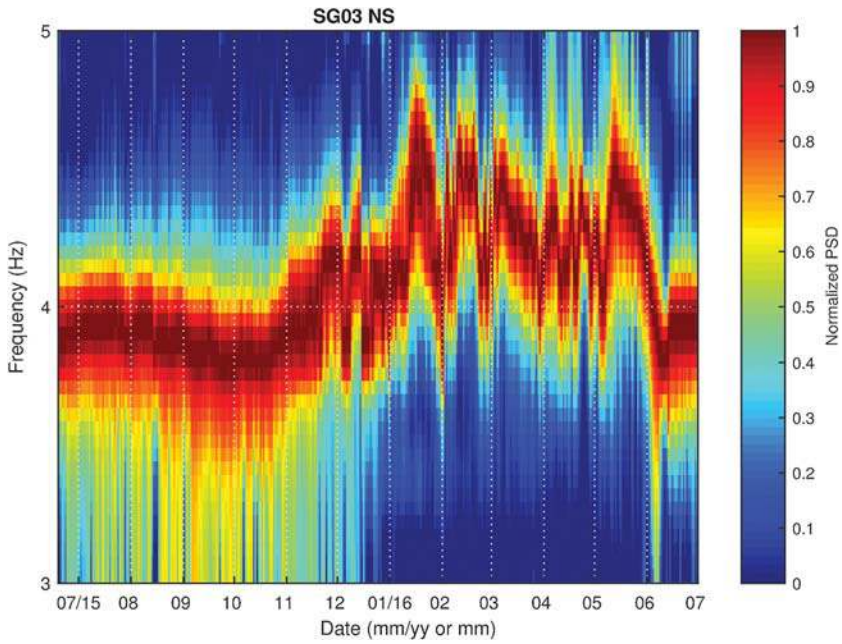

Figure 5. Time evolution of the normalized power spectral density computed between 3 and 5 Hz from the northwest component of the SG03 station located in the middle of the dam's crest. Two very different periods can be identified: a first one where the apparent fundamental dam frequency is stable, varying only slightly around 3.9 Hz, and a second one where the frequency is varying quite abruptly in the range [3.9–4.7] Hz.

couples of stations grouped in different interdistance bins. The lagged coherency was computed following Abrahamson (2007), after selecting the strong phase time window of each signal according to the values of the Arias intensity and aligning the signals based on their maximum cross-correlation lag times (see Koufoudi *et al.*, 2017, for details). The lagged coherency curves were further smoothed using a 1-Hz-wide averaging window for cosmetic reasons. Figure 7 shows that the phase of the motions at the dam–rock interface is slightly more variable than motions away from the dam, especially in the frequency range of the dam's eigenvibrations.

This could be caused by the effects of local topography along the dam–rock interface and by the response of the dam itself. A more comprehensive analysis of those measures is presented in Koufoudi *et al.* (2017). It is shown in particular that although sharp variations in both phase and amplitude variability are expected around the dam's eigenfrequencies along the dam–rock interface, the overall variability of the input motion to the dam can still be satisfactorily predicted by coherency models derived from free-field flat array data.

SUMMARY AND PERSPECTIVES

The Saint-Guérin seismological array operated in continuous mode during 1 yr from June 2015 to June 2016 and provided a unique dataset to study the response of a simple concrete arch dam, which will be accessible to the seismological and engineering community from June 2019. Using high-sensitivity intermediate period seismometers and large dynamic range digitizers, a set of high-quality recordings of 55 weak-motion events was acquired during the first six months period of the experiment, where all 19 stations were operating, despite the low seismicity level of the area. Those recordings allowed preliminary analyses of the spatial variability of seismic ground motions at the dam–rock interface in the linear regime (see Fig. 7 and Koufoudi *et al.*, 2017, for more details).

The continuous recordings of the Saint-Guérin experiment should prove useful to better understand the causes of the fluctuations of the resonance frequencies of the dam (see Fig. 5), and more generally to identify the modifications of the dam's mechanical properties induced by the environmental forcing factors such as water level or temperature variations. They should also be analyzed to track and monitor apparent velocity variations, within the dam or its surround-

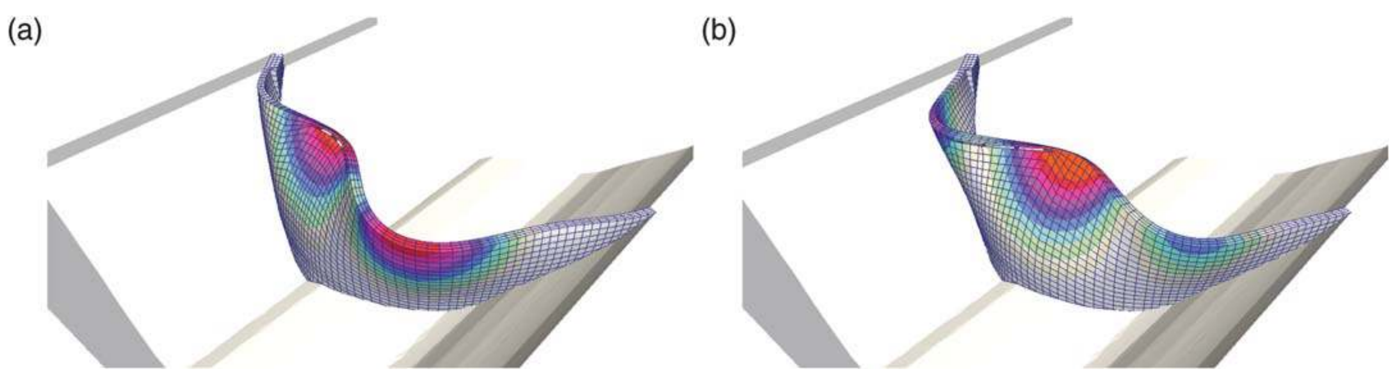

Figure 6. First two eigenmodes computed using a finite-element analysis of a simplified model of the Saint-Guérin dam. (a) The lower mode at 3.8 Hz corresponds to an antisymmetric displacement across the center of the dam's crest, and (b) the next mode at 3.9 Hz corresponds to a symmetric displacement.

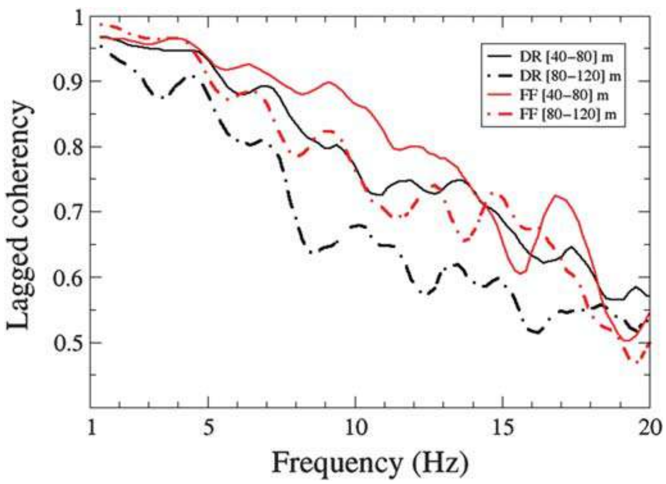

Figure 7. Median values of lagged coherency measured on the north–south component for all pairs of stations with interdistance between 0 and 40 m (solid curves) or between 80 and 120 m (dashed–dotted curves). Black curves correspond to measures performed along the dam–rock interface (referred to as DR on the plot) and the red to measures in the free field (FF).

ings, measured from the correlations of seismic ambient noise between the different couples of stations.

DATA AND RESOURCES

The full dataset will be accessible through the Réseau Sismologique et Géodésique Français (RESIF) website from June 2019. The FDSN network code of the experiment is YI (2015–2016), and the full citation information is E. Chaljub (2017), Saint-Guérin Arch Dam Experiment, 2015–2016, code YI, doi: 10.15778/RESIF.YI2015, funded by chaire Pereniti (Grenoble INP, EDF), Université Grenoble Alpes, instrumented by RESIF-SISMOB. Terrestrial seismic network. The catalog of earthquakes mentioned in this article was obtained from the French seismic monitoring network RÉNASS (Réseau National de Surveillance Sismique): http://renass.unistra.fr (last accessed January 2018). The eigenfunctions presented in Figure 6 were computed with the finite-element software code_aster, which is available under GNU General Public Licence v.3 at https://www.code-aster.org/spip.php?rubrique21 (last accessed January 2018).

ACKNOWLEDGMENTS

The authors are grateful to the French national pool of portable seismic instruments, Réseau Sismologique et Géodésique Français (RESIF)-SISMOB, of the French National Research Center, CNRS-INSU, for providing the sensors and data loggers used in the experiment. RESIF is a Research Infrastructure of the French Ministry of Higher Education and Research, which is managed by a consortium of 18 Research Institutions and Universities in France, and supported by a public grant from the French National Research Agency as part of the "Investissements dAvenir" program (reference: ANR-11-EQPX-0040). The authors thank Éric Bourdarot (CIH) for making the instrumentation of the Saint-Guérin dam possible, Yves Falcoz, and Julien Salviato (EDF) for providing a secure access to the dam facilities throughout the experiment, David Wolyniec (ISTerre) for his help in preparing the data and metadata, and all the people from ISTerre, 3SR, and CIH who helped during the installation and removal phases of the experiment. Work performed thanks to the support of EDF in the context of Chair PERENITI run by the Fondation Partenariale Grenoble INP. Partners responsibility of the Chair cannot in any circumstances be blamed on the grounds of the content of the publication, which is only binding its authors.

REFERENCES

Abrahamson, N. (2007). *Program on Technology Innovation: Effects of Spatial Incoherence on Seismic Ground Motions*, EPRI, Palo Alto, California.

Koufoudi, E., E. Chaljub, F. Dufour, P.-Y. Bard, N. Humbert, and E. Robbe (2017). Spatial variability of earthquake ground motions at the dam-foundation rock interface of Saint Guérin: Experimental and numerical investigations, *Bull. Earthq. Eng.* 1–27, doi: 10.1007/s10518-017-0266-8.

Larose, E., S. Carrière, C. Voisin, P. Bottelin, L. Baillet, P. Guéguen, F. Walter, D. Jongmans, B. Guillier, S. Garambois, *et al.* (2015). Environmental seismology: What can we learn on earth surface processes with ambient noise? *J. Appl. Geophys.* **116,** 62–74.

Yang, J., F. Jin, J.-T. Wang, and L.-H. Kou (2017). System identification and modal analysis of an arch dam based on earthquake response records, *Soil Dynam. Earthq. Eng.* **92,** 109–121.

Zerva, A. (2009). Spatial variation of seismic ground motions, in *Modeling and Engineering Applications*, CRC Press, Boca Raton, Florida, 42–62.

Eleni Koufoudi
Frédéric Dufour
Université Grenoble Alpes
CNRS, Grenoble Institute of Engineering (INP),
3SR 38000 Grenoble
France

Emmanuel Chaljub
Isabelle Douste-Bacqué
Sandrine Roussel
Pierre-Yves Bard
Eric Larose
Laurent Baillet
Université Grenoble Alpes
Université Savoie Mont Blanc
CNRS, IRD, IFSTTAR,
ISTerre 38000 Grenoble
France

Nicolas Humbert
Électricité de France
EDF-CIH
73370 Le Bourget-du-
Lac France