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# EXPERIMENTAL INVESTIGATION OF SPATIAL VARIABILITY OF GROUND MOTIONS – MONITORING OF AN ARCH DAM

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## *Abstract*

The term “spatial variability of seismic ground motions” denotes the differences in amplitude and phase content of seismic motions recorded over extended areas or within the dimensions of a structure. The effect of such spatial variability on the response of civil infrastructure systems such as dams is still an open issue. In-situ experiments may be helpful in order to answer the questions regarding both the quantification of the spatial variability of the ground motion within the dimensions of a structure as well as the effect on its dynamic response. For this purpose, the 69-m-high double curvature Saint Guérin arch dam located nearby the village of Beaufort, Savoie, France as well as the surrounding area is instrumented with a seismological network with a few meters of inter-station distance. This very dense network consists of nineteen velocimeters which have been deployed for one year in total (June 2015 - June 2016). The configuration of the network is such that the spatial variability of the ground motions can be captured on the dam-foundation rock interface (left and right side of the valley) and at the surrounding area. Coherency functions are computed and analyzed providing information about the effect of the on-site topography and the interaction with the dam on the ground motion. Besides, the measurements along the crest provide informations on the structure’s response that might be useful for the interpretation of the results.

*Keywords: dense seismic array; spatial variability; ground motions, arch dams*

## 1. Introduction

The observed difference in seismic ground motions recorded at different locations over extended areas or within the dimensions of an engineered structure within a short distance (e.g. within the dimensions of typical extended structures as the dams) is simply termed as spatial variation of earthquake ground motions (SVGM). It refers to the differences in amplitude and phase of seismic motions. Since the 1960's, pioneering studies analyzed the influence of the spatial variation of the motions on above-ground and buried structures. However, this scientific field only attracted extensive research interest about four decades ago with the installation of several strong motion instrument arrays. The seismological recording coming from dense seismograph arrays provide valuable information in understanding and therefore modeling SVGM. Nowadays, many permanent and temporary dense arrays are installed at various sites around the world. The Imperial Valley array [1] was one of the first few to be deployed; SMART-1 array [2] is one of the most investigated ones; some other arrays are the Chiba array [3], the USGS Parkfield array [4] and the Pynion Flat Array [5]. The majority of these arrays were located at uniform ground conditions, mostly at soil sites. Most of the studies use a stochastic approach (coherency estimation) to model SVGM during the prominent strong-motion shear wave window. Studies so far have observed a loss of coherency with increasing frequency and inter-station distance.

Engineering structures cross sites with irregular subsurface topography and ground types. Such sites give rise to the formation of surface waves that can lead to large amplifications, loss of coherency and significant ground strains in the wave-field (e.g. [6]; [7]; [8] etc.). The effect of such spatial variability on the behavior of civil infrastructure systems such as dams is still an open issue. Complex topographic effects, that are present in the case of arch dams, and the non uniform reservoir geometry give rise to additional causes for the spatial variability of the motions ( [9], [10], [11]). Recent studies, conducting linear and non-linear dynamic analysis of arch dams, point out that non uniform input motions at the base affect the patterns of the principle stress contours and crack profiles and modifies the tensile stresses and crest displacements ([12], [13], [14], [15], [16] etc). However, in current engineering practice, the ground motion excitation across the foundation of an arch dam is assumed to be spatially uniform, which becomes questionable for spatially extended structures in the near-fault region or on sites with inhomogeneity in surface geology and geometry.

The lack of in-situ experiments within the dimensions of a large structure with continuous points along the foundations, like arch dams, limits the understanding and thereafter the quantification of the SVGM. For this purpose, a seismological experimental campaign took place, for the period of one year, on and around the arch dam located in the site of Saint Guérin, a region of moderate seismicity. The double curvature Saint Guérin arch dam, located nearby the village of Beaufort, Savoie, France, as well as the surrounding area is instrumented with a very dense seismological network with a few meters of inter-station distances. The goal of this array is to collect data in order to identify the effective input motions as well as the free-field motions. It aims at monitoring the overall dam behavior during seismic events and at identifying the response patterns and governing effects during earthquakes. The records obtained at numerous locations of the arch dam could eventually be used in order to perform realistic dynamic analysis for the purpose of safety assessment of existing and future dams. The dense array in Saint-Guérin can be used to establish the necessary set of records covering dam excitation and response.

The seismo-tectonics, seismicity and geology of the Saint Guérin site, where the arch dam is located in, are firstly described. Thereafter, an overview of the seismological experiment is provided as well as a preliminary catalog of the selected recorded earthquakes used for the analysis that follows. Taking advantage of the in-situ measurements obtained from the experimental campaign, several analysis are performed in order to better understand the observed spatial variability of the ground motions and the output variability of the response of the dam. Herein, the "lagged coherency" of the ground motions [17] is quantified for each station-pair within the array at the dam-foundation rock interface and on the free field. The dependence of coherency on various source parameters is also investigated. The findings of the present research intend to contribute in enhancing the understanding of spatial variability of ground motions. It intends to be helpful in order to answer the questions regarding both the quantification of the spatial variability of the ground motion within the dimensions of an arch dam as well as the effect on its dynamic response. This work also opens up new insights and many questions in need of further investigation.

## 2. Dense seismological array in Saint Guérin site

### 2.1 Seismo-tectonics

The experimental campaign is taking place in the region south of Beaufort village, Savoie, northern French Alps, in France, where the dam of Saint Guérin is located. The earthquake activity along the Alpine chain is confined within two arcs: The Briançonnais and the Piemont seismic arc. As estimated in [18], the seismic rate of the Briançon area, which covers the southern tip of Briançonnais arc and it is its most active part, is low (1 earthquake of magnitude 5 with return period of 10 years). The geodetic displacement of the region, as estimated by GPS measurements is of the order of 1 mm/yr [18].

### 2.2 Saint Guérin arch dam

Saint Guérin dam is a double curvature arch dam, made of concrete, of 69 m height and 250 m crest length. The owner of the dam is the Électricité de France (EDF). Its construction started in 1957 and the structure was completed in 1961. The thickness of the crest is 3.10 m and the base thickness 12 m. The dam has a total volume of 65000 $m^3$ and its retained water volume is 13.5 $km^3$. Furthermore, this dam has a very simple design with no intake power station and is in a perfect state. A view of the arch dam is presented in Fig. 1. The site around the dam consists of limestone, indicating shear-wave velocities ($V_s$) higher than 2000 m/s.

Fig. 1 – Double curvature, 69 m high and 250 m long arch dam in Saint Guérin

### 2.3 Dense Seismological array

On the double curvature arch dam of Saint Guérin as well as on its surrounding area a very dense seismological array has been deployed. The array, installed by laboratories ISTerre and 3SR, consists of 19 stations. The stations were deployed both parallel and perpendicular to the axis of the valley. The configuration of the network firstly aims to capture the spatial variability of the ground motions on the base and on the dam-foundation rock interface (left and right side of the valley) therefore nine stations, SG01, SG05, SG06, SG07, SG08, SG09, SG10, SG11, SG12 were installed as shown in Fig. 2. Due to difficulties accessing the dam-foundation interface during the winter period, stations SG06, SG07, SG08, SG10, SG11 and SG12 were deployed for 6 months, until the end of December, while the rest till June. In order to get an idea of the response of the dam 3 stations were installed on the crest, SG02, SG03 and SG04. Three stations were located along the path that leads to the dam, along the axis of the valley, SG13, SG14 and SG15 in order to provide free-field SVGM data. Two stations, deployed on rock sites, aim to be used as references for the amplitude of the ground motion, SG17 and SG18. Finally, two stations were installed around the dam reservoir, SG19 and SG20 serving other scientific purposes. The configuration of all the stations of the seismological array is shown in Fig. 2.

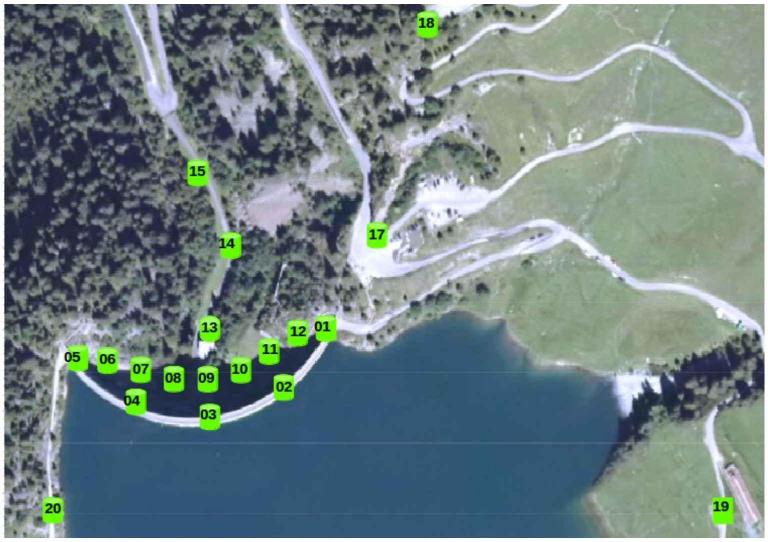


Fig. 2 – Location of seismological stations. Cylinders of different colors indicate the location of the stations.

The three sensors deployed on the crest of the dam are chosen to be of type Lenhartz 5s while the type of the rest of the sensors is Güralp CMG40T. All stations are connected to Nanometrics Taurus digitizers. Both sensors and digitizers belong to the French mobile national seismological pool INSU/SISMOB [19]. Sensors and digitizers are positioned in two different waterproof cases; the case that contains the sensor is isolated from the environment by a rock wool layer. The stations are connected to GPS antennas for the sake of synchronization.

## 2.4 Catalog preparation – Subset of events

Continuous records of about one year from all the installed stations are considered for catalog preparation. The catalog of ReNass [20] is used to identify the origin time and characteristics of the earthquake events in the broader area. Based on this catalog, probable seismic events are first identified from the continuous records through visual inspection. Over the first six months of the deployment of the seismological array in Saint Guérin, more than 100 local and regional events within 250 km distance from the array and having magnitude from 1.5 to more than 4, occurred in the broader Alpine area.

A subset of 67 events with signal-to-noise ratio higher than 3 in the frequency range [1 10] Hz, recorded by the stations of the dense network, is selected for the analysis of the spatial variability of the ground motion. Most of the events are shallow crustal and the maximum recorded PGV in the free field is $\sim 1.5 \times 10^{-5}$ m/s. Fig. 3 shows the location of the subset of events selected and Fig. 4 the distribution of the magnitude of the events as a function of their epicentral distance from the dam, their hypocentral depth and their azimuth. As shown in Fig. 3 and 4 the homogeneous distribution in terms of azimuthal coverage cannot be achieved due to locations of the earthquakes; the vast majority of the events occurred north-east and south-east along the Alpine arc.

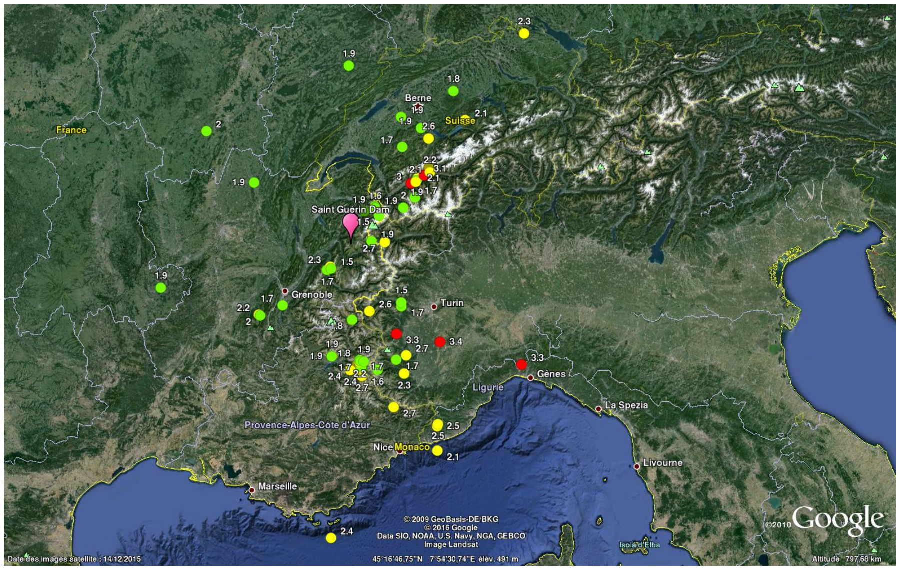


Fig. 3 – Map of the subset of 67 events, recorded from the seismological array during the period of six months (June 2015- December 2015). Green circles represent event locations with $M_L$ [1.5 2), yellow circles $M_L$ [2 3) and red circles $M_L$ [3 4,1]. The pink balloon indicates the location of the arch dam.

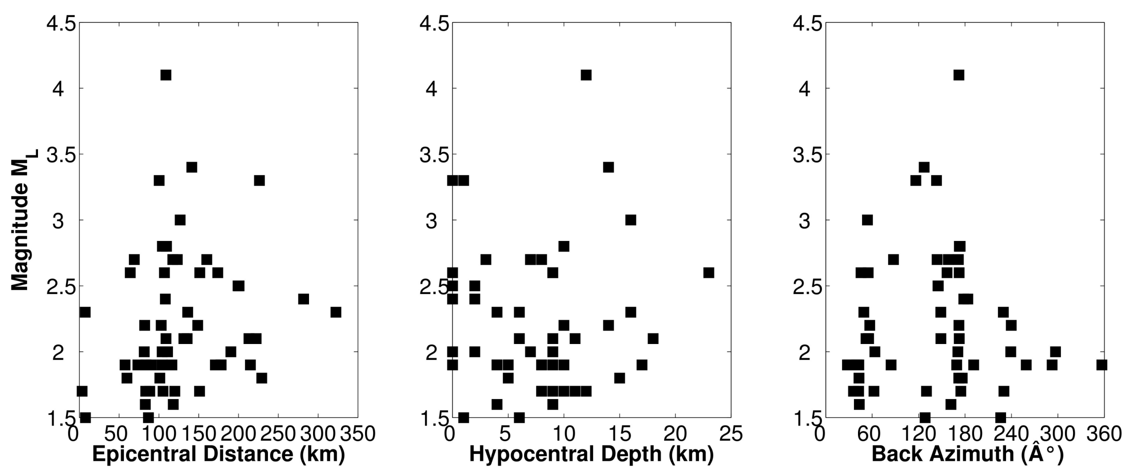


Fig. 4 – Magnitude distribution, $M_L$, as a function of epicentral distance (km) (left), depth (km) (middle) and Back Azimuth (°) for the subset of 67 events selected for analysis.

## 3. Spatial variability analysis

### 3.1 Coherency analysis

Coherency estimation is a stochastic approach widely used to model the spatial variation of the motions during the prominent strong-motion shear wave window. By definition, coherency characterizes the variation in Fourier phase and expresses the loss of correlation between two time series. The lagged coherency, of the seismic motion between the stations j and k is given by the modulus of the ratio of the smoothed cross-spectrum of the two time series to the geometric mean of the respective, identically smoothed, auto power spectra. The value of lagged coherency is zero for uncorrelated processes and it is equal to one for linearly correlated processes.

$$\left|\bar{\gamma}_{jk}(\omega)\right| = \frac{\left|\bar{S}_{jk}(\omega)\right|}{\sqrt{\left|\bar{S}_{jj}(\omega)\bar{S}_{kk}(\omega)\right|}} \tag{1}$$

For the evaluation of the lagged coherencies, different Hamming windows can be used (for example 3-, 7-, 11-, 15-, 19-point Hamming window) [17]. In [4] it is noted that the choice of the smoothing window should be directed not only from the statistical properties of the coherency, but also from the purpose of which it is derived. In evaluating an optimal window for the estimation of the coherency, in [4] it is suggested an 11-point (M = 5) Hamming (spectral) window, if the coherency estimate is to be used in structural analysis, for structural damping coefficient 5%, and for time windows less than approximately 2000 samples. Smoothing over a large number of frequencies gives poor resolution in frequency, but leads to small bias and small variability. Smoothing over a larger number of frequencies leads to robust coherency estimates, but poor resolution. For this analysis, an 11-point frequency smoothing is selected.With the assumption of homogeneity, stationarity and ergodicity, it is a common practice to choose some specific time windows, usually the shear (*S*-) wave part of the seismograms, to estimate the coherency function [17]; in most cases the shear wave carries the strongest energy in earthquake recordings and, generally, is the most damaging component from the engineering point of view. The selected time window is seen as a segment of a stationary process with limited duration. Herein, the *S*- wave part is identified based on the duration of the normalized Arias Intensity (I) of the two horizontal components of velocity as described in [5]. The two time histories for each couple of stations are aligned using the time lag that leads to the largest correlation of the two ground motions. Thus this coherency measure is assumed to remove the effects of systematic delay due to the simple inclined plane wave propagation, often called as the wave-passage effect.

Lagged coherency is estimated for the two horizontal components of the recorded data and for each possible combination of pairs in the array grouped in two categories for each event. The first group consists of the stations located on the dam-foundation rock interface e.g SG01, SG05, SG06, SG07, SG08, SG09, SG10, SG11 and SG12 while the second group consists of stations located in the free field (along the path leading to the dam) e.g SG13, SG14 and SG15. Firstly, the median estimates of lagged coherency of all the pairs of stations within a distance bin for each event are found. Coherency curves of some pairs are missing because some station recordings are not considered for some of the events due to either lack of recordings or low signal to noise ratio. Then the global median estimate of all the events is calculated. Four distance ranges are considered e.g [0 40] m, [40 80] m, [80 120] m and [120 160] m. The results are presented in Fig. 5. Black, solid and dashed, lines correspond to the pairs on the dam-foundation rock interface and red, solid and dashed, lines to the pairs of stations at the free field.

Generally, the spatial variability is small for low frequencies and large for higher frequencies validating that coherency variability is frequency dependent (heteroscedastic). The decay of lagged coherency with increasing inter-station distance is also evident. In the free field the motions are well correlated up until 7 Hz with values of lagged coherency higher than 0.85 for both groups of separation distances, [40 80] and [80 120] m. Additionally, the lagged coherency estimates in the free field are almost identical for both horizontal components. On the dam-foundation rock interface the motions exhibit higher variability than in the free field, especially for inter-station distances higher than 80 m. The variability for these inter-station distances is significant reaching values of lagged coherency equal to 0.6 at higher frequencies. In the NS component, the main direction of the dam's motion, the coherency loss is more significant than in the EW component; although the observed trends for the two horizontal components are comparable, more significant differences are identified in certain narrow frequency ranges. The NS component seem to exhibit a sudden loss of coherency in between three narrow frequency bands e.g around 2,5 Hz, 5 to 6 Hz and 7.5 to 9.5 Hz. The EW component of the motion exhibit a loss of coherency in the narrow band between 3 and 4 Hz, although much less significant than the loss of coherency of the NS component.

Analyzing one hour of ambient noise recorded at the three stations located on the crest of the dam e.g. SG02, SG03 and SG04, several eigen frequencies of the dam have been identified. The orientation of the dam is in the EW direction thus the energy of the dam's eigen modes is mainly in the NS direction. The vibration frequencies in the range of [1 10] Hz are similar for both horizontal components; the lowest one around 2.6 Hz, a second one around 3.9 Hz, a third around 5.1 Hz and a last one around 8.9 Hz. These frequencies may vary depending on the reservoir level and the thermal loading on the dam. The sudden loss of coherency for both horizontal components is occurring around the frequencies of vibration of the dam; in the NS comp. the sudden loss of coherency is occurring around the1st, 3rd and 4th frequency of vibration while in the EW comp. around the 2nd frequency of vibration. The main causes of spatial variability of the ground motions are identified in [7] as the wave passage effect, the extended source effect,the scattering effect and the local site conditions. The loss of coherency both with inter-station distance and with frequency is more significant along the dam-foundation rock interface with respect to the free field. The frequency ranges within which there is a sudden loss of coherency coincide with the frequencies of vibration of the dam. Moreover, in the NS component, the main direction of the dam's motion, the coherency loss is more significant than in the EW component. These observations suggest that the presence of the structure in addition to the local topography where the dam is located contribute to a further loss of coherency. Further research is ongoing in order to identify the contribution of each effect, local topography and soil-structure interaction, on the loss of coherency.

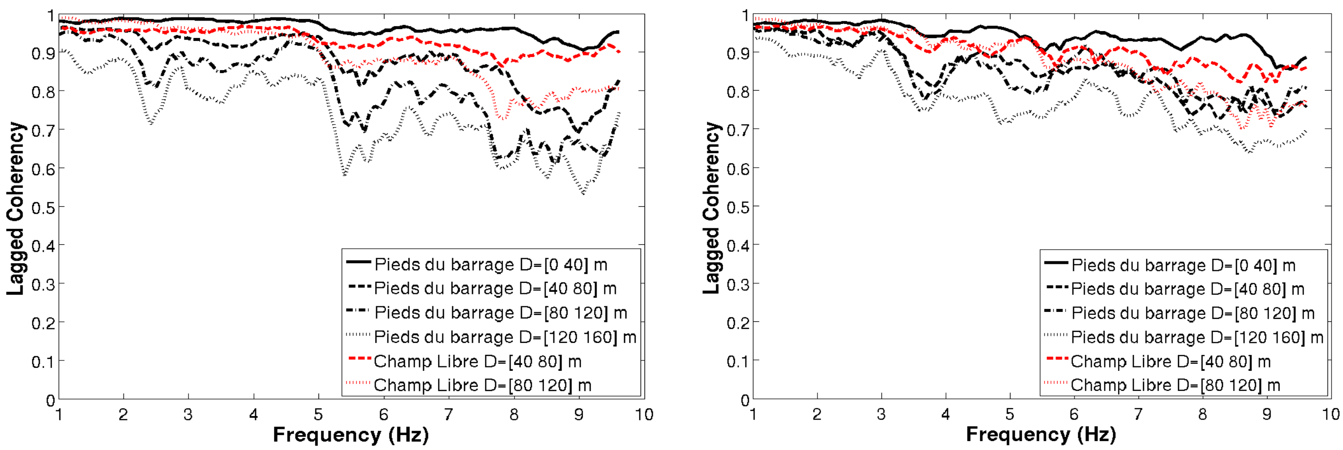


Fig. 5 – Estimated lagged coherency as a function of frequency for the NS (left) and EW (right) component; the median value of all the events within each distance bin along the dam-foundation interface (black lines) and on the free field (red lines).

### 3.2 Sensitivity analysis of coherency

The observed variability may be significant from earthquake to earthquake, and it is difficult to draw conclusions from observations on single events. Thus it is important to investigate the dependency of coherency analysis on various source parameters (magnitude, source to site distance and back azimuth) based on average values derived from a sufficiently large and representative set of events For such an averaging process, as for any kind of statistical analysis on the coherency estimates, normally distributed data is preferable. The variance of coherency depends on its value: as lagged coherency increases, its variance increases [21]. Therefore, a ATANH (or, $\tanh^{-1}$) transformation is applied to the coherency estimates to produce approximately normally distributed data about the median value [5]. The residuals of each individual median value from the global median value are estimated. In order to seek the magnitude dependence, the subset of events is divided into two epicentral distance groups, 0-125 km (39 events) and 125-250 km (28 events). Fig. 6 shows the residual plots of the ATANH coherency estimations of the NS (up) and EW (down) components as a function of magnitude, for different inter-station distance groups and frequency ranges. Similarly, the events have been grouped into two magnitude ranges, M 1,5-2,5 (50 events) and M 2,5-4,1 (17 events) to examine the distance dependence. Residuals of ATANH coherency values (NS and EW components) of the two magnitude groups of events are presented in Fig. 7 as a function of the corresponding epicentral distances for increasing inter-station distances and frequency ranges. Finally the back azimuth dependence is examined for increasing inter-station distances and frequency ranges for the two horizontal components in Fig. 8. No clear magnitude, source to site distance or back azimuth dependence is identified. No systematic difference is observed between the coherency estimates of the two horizontal components either. The observations of the present study are in accordance with the conclusions in [5] that when larger data sets are used,dependence on source parameters does not remain. Ongoing work is performed in order to identify the dependence of coherency on the topography and soil-structure interaction.

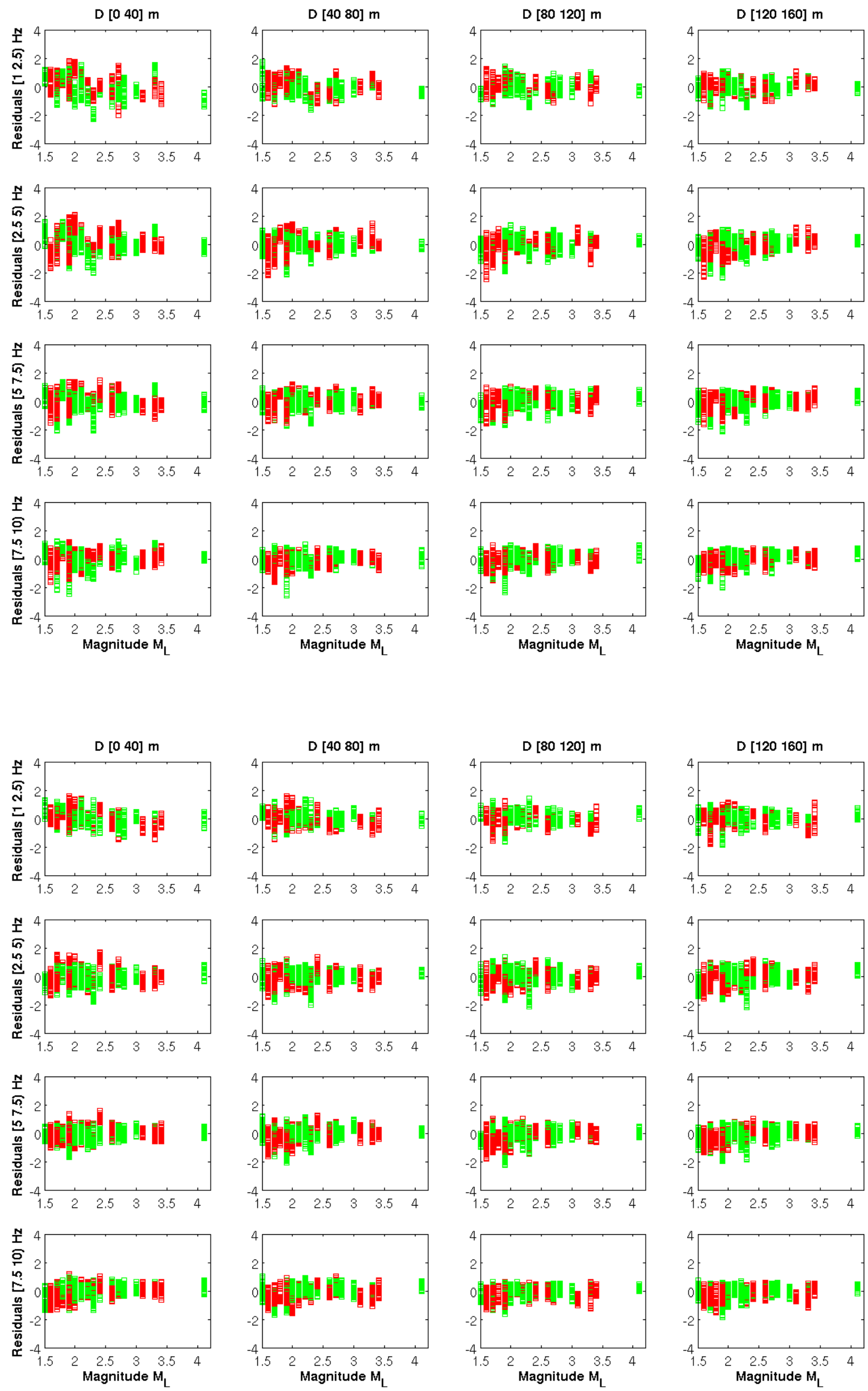


Fig. 6 – Coherency residuals of individual median estimates of ATANH(Lagged) coherency for each event with respect to the global median (ATANH units) of all the events as a function of magnitude of the NS (up) and EW (down) component for epicentral distance bins of D [0 125) km (green) and D [125 250] km (red) .

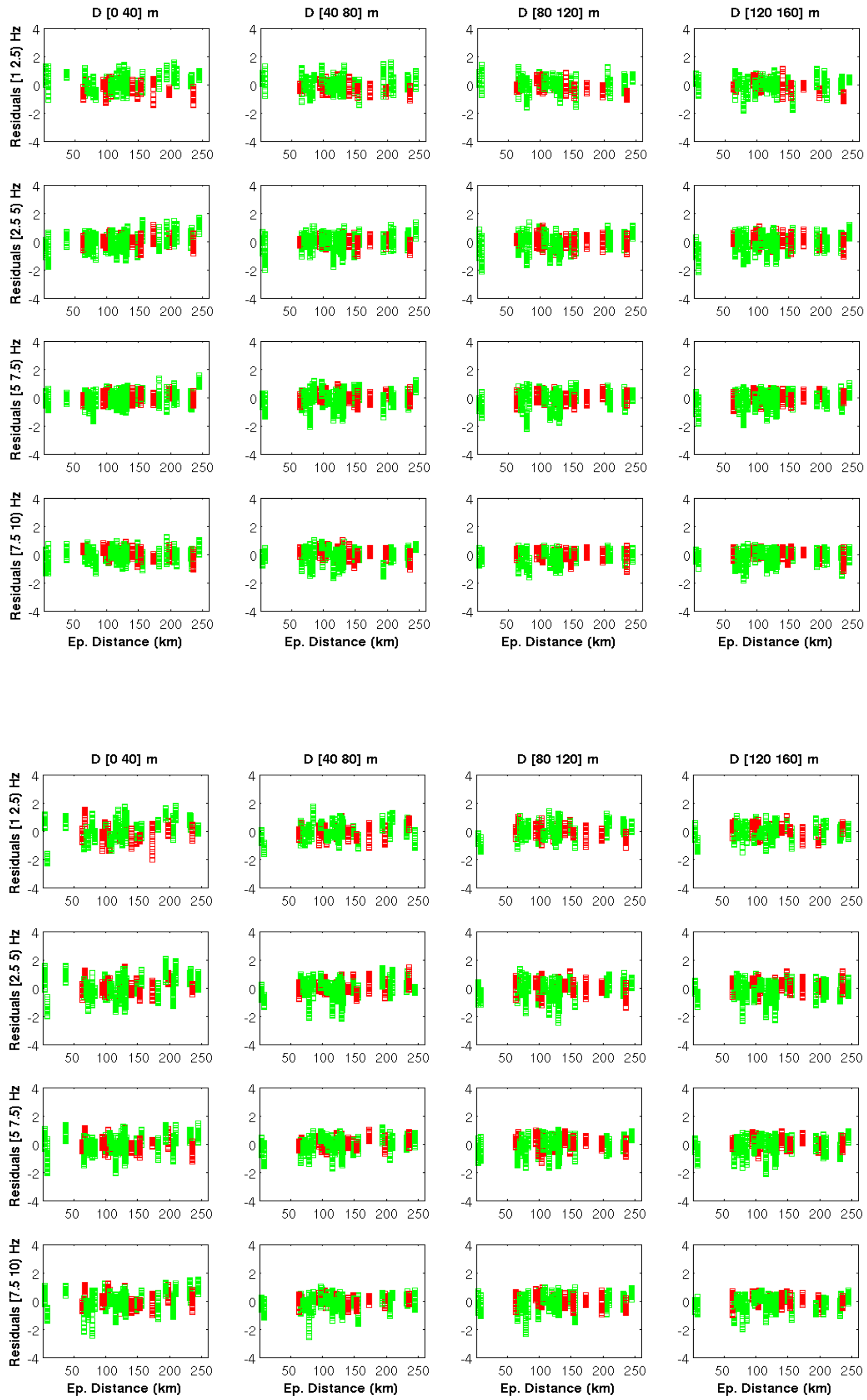


Fig. 7 – Coherency residuals of individual median estimates of ATANH(Lagged) coherency for each event with respect to the global median (ATANH units) of all the events as a function of epicentral distance of the NS (up) and EW (down) component for magnitude bins of M [1,5 2,5] (green) and M [2,5 4,1] (red).

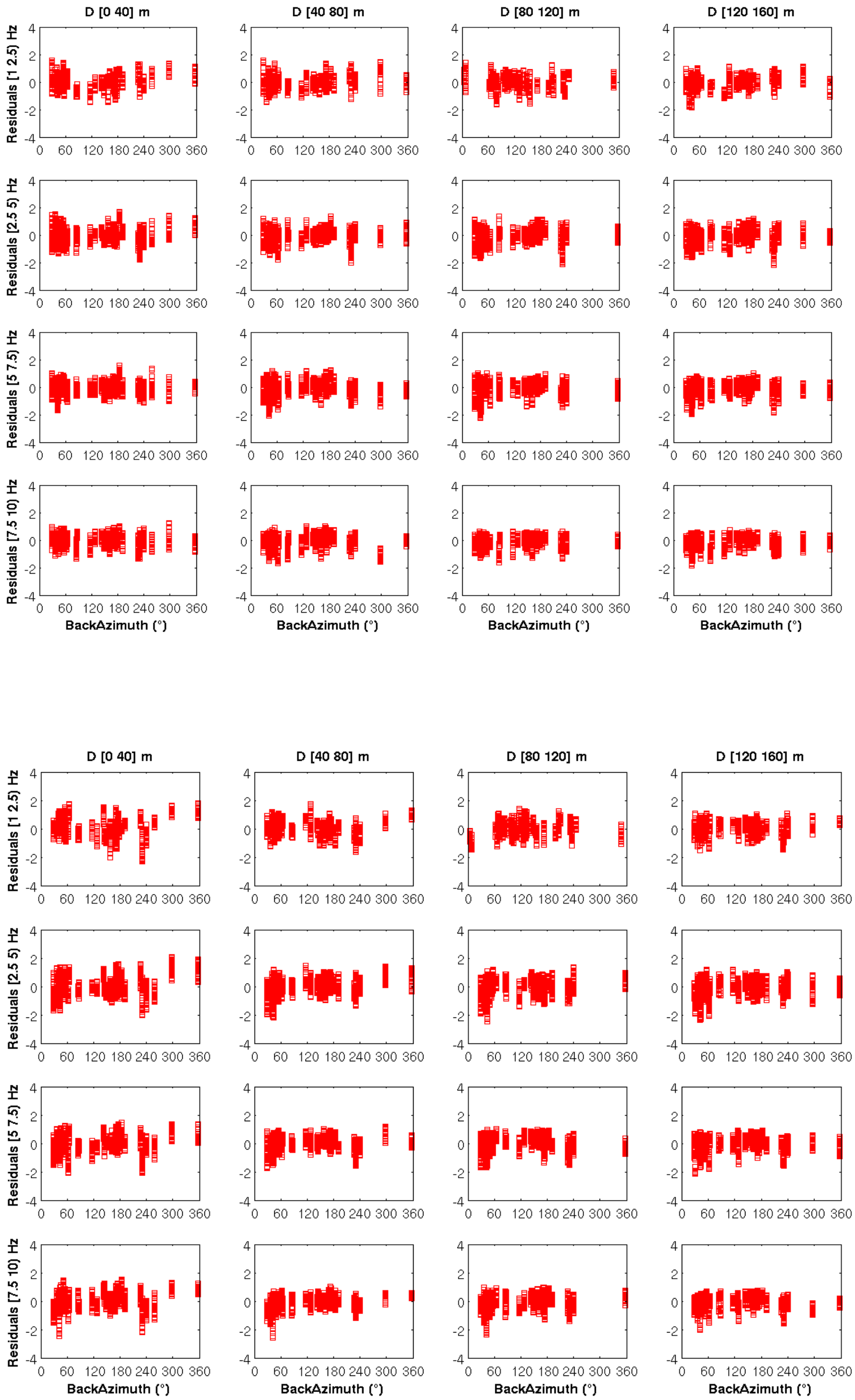


Fig. 8 – Coherency residuals of individual median estimates of ATANH(Lagged) coherency for each event with respect to the global median (ATANH units) of all the events as a function of back azimuth of the NS (up) and EW (down) component.

## 4. Conclusions

This study presents a seismological experimental campaign that has taken place on and around Saint Guérin arch dam over the period of one year. A subset of 67 recorded earthquakes is selected for further analysis. The phase variability of the ground motion at the dam-foundation rock interface is found by estimating lagged coherency of all possible pairs among nine stations with inter-station distances ranging from 13 to 160 m. Additionally, the spatial variability in the free field is estimated based on the three stations located on the path leading to the dam. The coherency is estimated using the S- wave part of the seismograms, identified based on the Arias intensity. The median values of lagged coherency for all pairs of stations with separation distances 0-40 m, 40-80 m, 80-120 m and 120-160 m respectively are computed in the frequency range [1 10] Hz for both horizontal components. Coherency estimates for both horizontal components in the free field and on the dam-foundation rock interface decay with increasing frequency as well as with inter-station distance. The ground motions in the free field appear to be more correlated along the frequency range with values generally higher than 0.85 with the respect to the motions at the interface of the soil with the structure. In the latter case, the variability of the motions is higher with values of lagged coherency reaching down to 0.6. The two horizontal components show similar trends although the motions in the NS direction, the principle direction of motion of the dam, are less coherent. The observation that the motions are significantly more variable on the dam-foundation rock interface than in the free field indicate that the local topography where the dam is located as well as the soil-structure interaction effect contribute notably to the loss of coherency. Additionally, the frequency ranges where the loss of coherency is sudden and more significant coincide with the frequencies of vibration of the dam thus the soil-structure interaction effect could explain the sudden higher variability. Further research is ongoing aiming to better identify the contribution of both topographic and soil-structure interaction effect. Finally, for the sake of statistical analyses an ATANH transformation is applied to the results to produce approximately normally distributed data around the median value in order to summarize the observed tendency of coherency with three source parameters, named magnitude, site-to-source distance and back azimuth of the events. No systematic dependence of coherency is observed on either of the three source parameters.

Throughout the present study the importance and necessity of the in-situ measurements for the better understanding of the phenomenon of spatially variable ground motion becomes evident. The collected data from the Saint Guérin seismological array are used to identify the variable effective input motions, compare them with the free-field motions and point out the topographic and soil-structure interaction as governing effects of the variable motion. Additionally, the records are helpful in order to extract key dynamic properties of the dam-reservoir-foundation systems such as the frequencies of vibration. Finally, the experimental campaign will be used to establish a set of records covering dam excitation and response that eventually will be used to calibrate finite element earthquake analysis.

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