RESPECTIVE ADVANTAGES OF SURFACE AND DOWNHOLE REFERENCE STATIONS FOR SITE EFFECT STUDIES: LESSONS LEARNT FROM THE ARGONET (CEPHALONIA ISLAND, GREECE) AND CADARACHE (PROVENCE, FRANCE) VERTICAL ARRAYS

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ABSTRACT

The use of seismological instrumentation is essential within the framework of site-specific seismic hazard studies. The “Standard Spectral Ratio” (SSR) method involves a reference station, located, if possible, at a rock or hard-rock site assumed to be free of site effects and a station located at the site to be analyzed. The choice of a reference station is not straightforward. Stations located on outcropping rock are the easiest. However, such sites are not always easy to find. One alternative solution is the use of borehole instrumentation, involving a downhole station, located at the bedrock underlying the softer sediment layers. However, downhole recordings are affected by downgoing waves reflected off the surface. In order to discuss the respective advantages of these two possible options of reference station, we analyzed records from two recently installed arrays. The first array is installed in Cephalonia Island (Greece) in an environment of very high seismicity. The second array is installed at the Cadarache industrial site (South East of France) in a low-to-moderate seismicity environment. The use of surface reference stations provides more straightforward site amplification estimation. It is worth also to mention that the positioning of the downhole sensor is not so easy to decide when the geological interpretation of borehole cores is ambiguous (i.e., hesitancy on whether the borehole did or did not reach the real, un-weathered bedrock). Nevertheless, the analysis of downhole sensors (or more generally, borehole arrays) allows accessing information that surface reference stations alone cannot address.

Keywords: Borehole array, Standard Spectral Ratios, Reference stations, Site effect, Argonet.

1. INTRODUCTION

The recording of earthquake ground motions at different site locations can provide valuable information on local site amplification and hence, is an important factor for site-specific seismic hazard studies. Basically, the most used method to measure amplification is the “Standard Spectral Ratio” (SSR) approach (Borcherdt 1970) that involves a reference station, located if possible at a rock or hard-rock site assumed to be free of site effects and a station located close to the site to be analyzed. However, the choice of a reference station is not straightforward. Stations located on outcropping rock are the easiest option in terms of installation constraints. However, such sites are not always easy to find (if not impossible), as for example in cases of very large basins (implying large distance between site and reference station), in cases of valleys with sharp topography on their sides (introducing risk of

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topographic effect at the reference station), in cases of weathered rock at surface (implying signal amplification at least at higher frequencies at the reference station). One alternative solution is the use of borehole instrumentation, involving at least one downhole station, located at the bedrock underlying the softer sediment layers. Such solution is logistically more difficult and expensive to implement. Moreover, downhole recordings are affected by downgoing waves from the surface which modify the surface-to-downhole spectral ratio with respect to a surface-to-surface spectral ratio (Bonilla et al., 2002; Field et al., 1997; Régnier et al., 2014).

In order to discuss the respective advantages of these two possible options of reference station (surface or downhole), we present two case-studies using records from two recently installed arrays: one installed in Cephalonia Island (Greece), in a very high seismicity area; the second one installed on the Cadarache industrial site (South East of France) in a low-to-moderate seismicity environment.

We will first present both installations (local geology, instrumental setup, used datasets). We will then show and comment basic SSR analysis involving both downhole and surface reference stations. An example of strong motion analysis aiming to highlight non-linearity will be discussed. Some examples of setup issues that can alter the quality of signal at high frequency will also be highlighted. Finally, empirical and simulated SSR will be compared and used to discuss how this comparison can help in the comprehension of geological features that locally cause the amplification.

2. SITES AND DATASETS DESCRIPTION

2.1 Argonet site

Cephalonia Island is located in the Ionian Sea, Greece (Figure 1), and it is one of the most seismically active regions in the Euro-Mediterranean area. Due to this high seismicity and the presence of a sedimentary basin, this area was chosen as a test site within the framework of the French National Research Agency PIA SINAPS@ project. A permanent accelerometric vertical network within the Koutavos basin, known as “Argonet” (Theodoulidis et al. 2018), has been installed with the long term objective to perform the validation of three-dimensional, non-linear computation of ground motion. The Koutavos basin is situated south of the town of Argostoli, the capital of the island. It is located on the southern shore of an elongated lagoon and is filled with Quaternary and Pliocene detritic deposits. This basin forms the heart of an active syncline (i.e., the Argostoli syncline) that is oriented NNW-SSE (Figure 1).

The Argonet array (Figure 2) is equipped with Kinematics accelerometers. It consists of one reference station at surface on rock (called AR0 in this paper) and one vertical array within the Koutavos basin (soil site) with one station at surface (called AS0) and four downhole stations located at the bottom of four different boreholes, at 5.6 m, 15.5 m, 40.1 m and 83.4 m depth, respectively (called AS6, AS15, AS40 and AS83). AS83 is assumed to be located in the bedrock. We will comment on the validity of this assumption later. The system runs since July 2014 (AS6 was installed later, in June 2015) in continuous mode (200 Hz sampling frequency) and earthquake events are retrieved from continuous records by association with seismicity catalogue and PGA threshold exceedance. The event dataset used in this paper covers the period from July 2014 to April 2017 and involved 436 very well recorded earthquakes from $M_L=1.6$ to $M_W=6.4$; with epicentral distances from 1 to 200 km.

The shear wave velocity profile below the Argonet soil site (AS) was estimated by various methods: cross-hole, downhole, surface-wave-based methods. Additional information was provided by seismic interferometry analysis using seismological data recorded at Argonet vertical array (unpublished results; see for example Roumelioti et al., 2018, for a description of the methodology). The $V_s$ profile shown Figure 3 is consistent with information provided by the various methods used (taking into account their own uncertainties) at least down to 83 m. Below this depth, larger uncertainties remain, especially concerning the exact position of the top of the cretaceous limestones that could be considered as the “geological” bedrock. The AS83 sensor is however located in stiff-soil to rock geological formation (sandstone) with $V_s$ around 800 m/s and can hence be considered as placed within the “geotechnical” bedrock (we call “geotechnical bedrock” the formations that are characterized by $V_{S30}>800$ m/s).

According to the best-estimated valuation provided by geologists, the “geological” bedrock (we call
“geological” bedrock the formations than are significantly older than the ones that compose the basin infilling: here this corresponds to cretaceous limestones) may be found around 90-95 m depth (called hypothesis 1), but another assumption, with a deeper limestone bedrock will be discussed later (hypothesis 2).

Figure 1. Location of Argostoli and Cadarache sites (centre top) and respective simplified geological maps of both sites (bottom). The rock surface site and the soil site with vertical array of the Argostoli area are noted as “AR” and “AS”, respectively (bottom left). The rock surface site and the soil site with vertical array of the Cadarache area are noted as “CR” and “CS”, respectively (bottom right).

Figure 2. Schematic illustration of instrumental setups of Argostoli (left) and Cadarache (right) sites, and pertinent geological information. All sensors deployed in Argostoli are accelerometers (Episensors from Kinemetrics). All sensors deployed in Cadarache are broad-band seismometers (CMG3T, CMG6TD, CMG40T borehole-SPB or borehole-flute from Guralp). ASxx means “Argostoli Soil site located at xx m depth”, CRyy means “Cadarache Rock site located at yy m depth”, etc. This figure is not to scale.
Figure 3. Shear wave velocities profiles of Argostoli (left) and Cadarache (right) sites and respective locations of sensors used in this study. The sensors denoted as “AS91*” and “AS110*” are “virtual” sensors to be used later for simulations. For both sites, two profile hypotheses will be discussed in the present study. The proposed profiles for Argostoli were derived from a joint interpretation of cross-hole, down-hole, surface-wave based methods and seismic interferometry analysis. The proposed profiles for Cadarache were derived from P-S suspension logging measurements.

Of course, the initial objective of the drilling operations was to go down to the cretaceous limestone bedrock. However, the first attempt of drilling down to the limestone ended in the breakage and the loss of an entire drilling pipe, associated to drilling water losses, water incomings, etc. This incident was attributed to a possibly strong karstic phenomenon (the Cephalonia Island is known for such phenomena, and the drillers expected and feared such an incident). Moreover, this possible karstic phenomenon was also interpreted as being the proof of the relative proximity of the cretaceous limestones. At that point, it was decided to ensure the second drilling attempt and stop it at ~83 m in order to at least ensure the attainment of the “geotechnical” bedrock (which will likely to be not so far from the “geological” bedrock). This kind of hazards should always be kept in mind when a downhole reference is considered.

As for the Argostoli rock site (AR), there is currently no processed data that provide velocity information exactly below the surface station. The proposed velocity profile (Figure 3) was derived from surface-wave-based methods carried out on a limestone outcropping area located 2.5 km southeast. The direct use of this profile comprises hypothesis 1, but another assumption, including a “faster” profile will also be discussed later (hypothesis 2).

2.2 Cadarache site

The Cadarache research Centre is located in Provence, close to the Alps (southeastern France) (Figure 1). The Alps are one of the most active seismic regions in mainland France, although the associated seismic activity is low to moderate. This site is characterized by massive cretaceous limestone outcrops, intersected by a relatively small paleovalley (a few hundred meters wide, 50-150 m deep) that is filled with stiff Miocene sand and sandstone, and softer quaternary deposits. This valley is oriented NW-SE.

The Cadarache instrumentation providing data used in this paper (Figure 2) comprises Gürahlp broadband seismometers located at two sites. The first one, on massive Cretaceous hard rock involves three stations: a first one (CR0) is located at surface (buried and firmly coupled to the ground), the second one (CR3) is placed within a seismic vault at a depth of ~3 m and the third one (CR45) is placed within a borehole at 45 m depth. The second site is located within the valley (soil site) and involves one station buried at surface (CS0); another station, also considered to be at surface, placed on a concrete slab within a man-hole at ~1 m depth (CS1); and three stations placed in three distinct boreholes at 6, 25 and 59 m depth (respectively CS6, CS25 and CS59). CS59 is assumed to be within
bedrock. Over this set of stations, CR0, CR45 and CS0 were temporary stations. The borehole stations at the soil site were also deployed progressively, so the operation time is variable from one station to the other.

The system records in continuous mode (100 Hz sampling frequency) and earthquake events are retrieved from continuous records by association with seismicity catalogue, and then carefully “manually” checked by a seismologist who also picks P- and S-waves arrival times. All events that show a signal to noise ratio higher than 3, at least within a narrow frequency band, were kept. The final event dataset used in this paper covers the period from July 2015 to March 2017 and involves 336 earthquakes from \( M_L = 0.8 \) to \( M_W = 7.9 \); with epicentral distances from 10 to 16400 km. More information about this site and dataset features can be found in Perron (2017) and (Perron et al. 2017a) (in these articles, the sites CR and CS are referred as sites P1 and P4, respectively).

Various methods have been carried out at both soil and rock Cadarache sites to derive velocity profiles. In particular, the CR site is one of the test-sites used within the framework of the InterPACIFIC project (see e.g. Garofalo et al. 2016). For the present work, we used the profiles provided by the P-S suspension logging (PSSL) method (Figure 3) that allows the highest vertical measurement

The choice of the depth of the deepest sensor at the soil site (assumed to be in bedrock) in Cadarache raised questions, as well, but in this case not due to technical limitations as for Argonet, but due to geological uncertainties. Before the drilling, the depth range of cretaceous limestone geological bedrock was estimated between 60 and 90 m. Hard breccia (but not limestones) were found around 59 m with an unexpected thickness (up to 95 m depth). Just below the breccia, large limestone blocks were found within a clay matrix (from 95 to 105 m) and then massive limestone was found below 105 m depth. The PSSL measurements showed very high S-wave velocities within limestone, but also within breccia \( V_S > 2000 \text{ m/s} \). As for the “limestone blocks in clay matrix” zone, even if the \( V_S \) provided by PSSL was lower (down to 500 m/s), the first hypothesis is to consider this zone as a near vertical fault. Normal faults are known in Cadarache and this assumption’s validity is plausible. The verticality of these faults associated to the verticality of the borehole could explain the apparent large thickness (10 m) of the observed zone. So, the first assumption discussed in this paper (hypothesis 1) considers this zone as laterally not representative, and the corresponding velocity profile interpolates high \( V_S \) values between breccia and limestone. The alternative possibility (hypothesis 2), that will also be discussed, rejects the fault assumption and considers the clayey zone as having a sedimentary origin. The lower velocity zone could, hence, be laterally extrapolated. For this latter hypothesis, the entire PSSL profile is considered.

3. SURFACE/SURFACE AND SURFACE/DOWNHOLE SSR

The datasets of both sites were used to compute different SSR (Borcherdt 1970) curves taking into account the signal-to-noise ratios. The selection of signal and noise time windows was performed using the methodology and the Matlab routines proposed by Perron et al. (2017b). All SSR means presented in this paper are geometrical means of different “single event” SSR values, based on at least 10 events kept for each computed frequency, using signal-to-noise ratios higher than 10 (for Argonet dataset) or 3 (for Cadarache dataset). More information about computational procedure and used methodology can be found in Perron (2017).

3.1 Surface/surface vs surface/downhole SSR

Figure 4 shows SSRs for both Argostoli and Cadarache sites, and for the use of both surface and deepest borehole stations as references. Logarithmic standard deviations are also shown. As for the Argostoli surface/downhole SSR (AS0/AS83), one can identify four resonance frequencies at 1.7, 3.6, 5.6 and 7.6 Hz, whereas on Argostoli surface/surface SSR (AS0/AR0), only two resonance frequencies can be clearly distinguished (1.6 and 3.2 Hz), slightly lower than the two first ones identified from surface/downhole SSR.
As for the Cadarache surface/downhole SSR (CS1/CS59), three resonance frequencies could be suggested within the computed frequency range (4.4, 9.9 and 15.4 Hz).
The Cadarache surface/surface SSR (CS1/CS3) does not show clear resonance frequency, but rather a flat amplification that is reached at the frequency of 3.4 Hz. This frequency is significantly lower than the first frequency identified on the surface/downhole SSR. On both sites, the standard deviations of downhole/surface SSRs are globally lower than the ones obtained for surface/surface SSRs. This observation can be attributed to the fact that the surface rock reference stations are more distant from site soil stations than the downhole stations. Furthermore, the possible topographic effects that may affect rock surface station could also increase variability.

### 3.2 SSR within vertical arrays

Figure 5 shows SSRs computed using only stations of the vertical arrays, with the deepest stations as references, for both Argostoli and Cadarache sites. Overall and as expected, considering at least the fundamental frequencies, we can observe that the amplification is larger for the shallower downhole stations. For higher resonance modes, this overall observation sometimes fails due to the downgoing wave destructive interference phenomenon as seen in the second harmonic (~3.6 Hz) of the AS15/AS83 SSR. The most evident exception to this overall observation is the difference between the CS0/CS59 and CS1/CS59 ratios at high frequencies, where the CS1/CS59 shows higher amplification (up to a 3-factor) than the CS0/CS59 that cannot be explained by the depth difference between CS0 and CS1 stations (only one meter). This feature will be discussed below.

### 3.3 Azimuthal analysis

Figure 6 shows an azimuthal analysis of SSRs at soil sites between surface and deepest downhole stations. For these SSRs, the horizontal motion is computed within different azimuths by rotation of east and north record components. As shown in Figure 6, a variation of amplification can be observed, especially in terms of frequencies. As first quantitative analysis, we searched for the azimuths that produce the highest and lowest amplification (depicted as $A_{A_{\text{max}}}$ and $A_{A_{\text{min}}}$ on Figure 6). Then, we found the azimuths that produce fundamental amplification peak at the highest or lowest frequency (depicted as $A_{A_{\text{max}}}$ and $A_{A_{\text{min}}}$ on Figure 6). For the Argostoli site, both $A_{A_{\text{max}}}$ and $A_{A_{\text{min}}}$ azimuths (~35° and 40°) roughly correspond to the direction perpendicular to the Argostoli syncline axis, which is consistent with what is expected in case of 2D geometry (“SV” polarization terms of 2D simulations).
Figure 5. SSR computed at different depths in the vertical arrays using the deepest sensors (assumed to be in bedrock or near the bedrock interface) as reference. **Thick solid lines:** geometric means; **thin dashed lines:** geometric standard deviation. **Left:** Argostoli site. **Right:** Cadarache site.

Figure 6. Azimuthal variations of SSRs and identification of the highest ($A_{f_{\text{max}}}$) and lowest ($A_{f_{\text{min}}}$) frequency of the fundamental resonance peak (**white squares**), as well as the highest ($A_{\text{max}}$) and lowest ($A_{\text{min}}$) amplitude of the maximum of the fundamental resonance peak (**white dots**). The **white arrows** point to the azimuths of minimum and maximum frequencies considering the overall shape of SSR azimuthal variation instead of point extremes. **Left:** Argostoli site. **Right:** Cadarache site.

The $A_{\text{min}}$ and $A_{\text{min}}$ azimuths, even if more dispersed, remain perpendicular to the previous direction and are roughly parallel to the axis of the Argostoli syncline ("SH" polarization terms of 2D simulations). For the Cadarache site, $A_{\text{max}}$ and $A_{f_{\text{max}}}$ azimuths (~75° and 90°), as well as $A_{\text{min}}$ and $A_{f_{\text{min}}}$ azimuths (~5° and 175°) cannot be related to the Cadarache valley axis and hence depict a more complex amplification context. However, if we refer to the overall typology of the variation versus azimuth of the empirical amplification (dashed white line on Figure 6), extrema more consistent with the valley orientation could be extracted (as for example the 35° azimuth for Cadarache site, that corresponds more clearly to the “SV” direction, perpendicular to the valley axis). This observation suggests that not only strict amplitude or frequency extrema should be considered on azimuthal analysis, but also the overall amplification response typology.

4. NON-LINEARITY IDENTIFICATION

Figure 7 shows two examples of strong motion effect on SSRs, addressing the observation of possible non-linearity. On this figure, SSR means and standard deviations (grey shaded areas) are first computed using 15 weak motion records that were selected selected for their short distance (maximum 5 km) from the strong motion earthquake locations. This selection of a subset of events allows reducing the possible bias due to site amplification variability associated to source location.
Indeed, this variability could be large (see e.g. Perron 2017). The SSRs computed with strong motions are drawn in orange on Figure 7.

The first analysis is done using the Lefkas $M_W = 6.4$ earthquake that occurred on November 17, 2015, at an epicentral distance of ~56 km and that produced a raw PGA of 143 cm/s² at AS0. This event is the strongest one (in terms of local PGA) of the whole current Argonet dataset. On the surface/surface SSR (AS0/AR0), a higher damping of high frequencies can be observed, and a slight shift toward low frequency of the resonance peaks, but this feature is not clear. On the surface/downhole SSR (AS0/AS83), the higher damping of high frequencies is also observed, but here, the frequency shift of the second peak is clearer.

The second analysis is done using a local $M_L = 4.4$ earthquake that occurred on September 19, 2016 at an epicentral distance of ~14 km and that produced a raw PGA of 138 cm/s² at AS0. This event produced the second strongest motion of the dataset, and the strongest motion recorded at AS6 (this sensor was installed later than the other ones). Although this event produced approximately the same PGA with the Lefkas event, the duration of the motion is shorter and its frequency content is less rich in low frequency content. Hence, this event is less susceptible to produce non-linearity. Considering AS0/AR0 and AS0/AS83 SSR, no non-linearity could be observed. However, considering the SSR between the surface and shallower borehole sensor (AS0/AS6), an overall frequency shift is clear, as well as a significant amplitude discrepancy. In order to explain why the AS0/AS6 SSR appears higher for the strong motion, it is worth to mention here that the $V_s$ within the two first meters below AS0 is higher than the $V_s$ at 6 m depth (Figure 3). This stiffer layer at surface is explained by the presence of the rubble of destructions caused by the major earthquake that occurred in 1953 in Cephalonia that were disposed in the Koutavos Park. Hence, we can suggest a possible non-linearity that occurred within the layers around AS6 sensor (the softer layers of the whole profile), non-linearity that could not be clearly identified using only surface (AS0) and deepest (AS83) sensors. This last observation indicates that vertical arrays of several sensors provide a large amount of information concerning the non-linear behavior of the soil that is likely to happen in the very shallow soil layers (e.g. Régnier et al., 2013).

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Figure 7. Top: SSR at the ARGONET site computed using the signals of the Lefkas earthquake $M_W = 6.4$ that reached a PGA of 143 cm/s² at AS0. Results are shown for soil to rock reference station (top left) and surface soil to deepest downhole (top right). Bottom: SSR computed using the signals of a local $M_L = 4.4$ earthquake that reached a PGA of 138 cm/s² at AS0. These strong motion SSRs (orange lines) are compared, as well, to the means and standard deviations of a set of weak motion signals (grey shaded areas) corresponding to smaller earthquakes that occurred within the same area of the strongest ones. Results are shown for surface soil to surface rock stations (bottom left), surface soil to deepest downhole (bottom center) and surface soil to shallow...
In addition, analyzing SSRs involving reference stations (surface or deepest downhole stations), the surface/downhole SSRs seem to show clearer frequency shifts that surface/surface SSRs. Furthermore, the use of several sensors within the whole profile between surface and bedrock allow to better identify a non-linearity that may have occurred within a given layer and that may not be observable using only surface and deepest downhole sensors.

5. SETUP ISSUES

Besides the reference station location, the choice of specific sensor installation practices creates observations that worth discussion. This is illustrated in the Figure 8. The first issue has already been mentioned in the description of the Figure 5 and is here illustrated as the SSR between CS1 and CS0. A large amplification (up to 3 between 20 and 25 Hz) is observed. These two stations are very close one from the other and no “site effect amplification” can be invoked to explain such discrepancy. No instrumental issue can be suspected here (numerous verifications were achieved with different sensor types on this site). The only difference between these two stations lies in their installation. CS0 was installed as a temporary station. It was buried right below the surface in full contact with the ground. After digging a hole and placing the seismometer, soil material was firmly compacted around the sensor, as it is usually done during a post-seismic survey. CS1 was installed as a permanent station and placed on a concrete slab, within a man-hole (at approximately 1 m depth, the concrete slab being uncoupled from man-hole walls, see Figure 2). We think that the observed amplification above 10 Hz is due to the concrete slab’s own resonance frequency. Therefore, the records of CS1 station are affected at high frequency by a kind of soil-structure interaction.

Figure 8 also shows SSRs involving stations deployed on the Cadarache rock site. The station CR3 is installed within a real seismic vault at ~3 m depth. In this case, the building of the seismic vault, as well as the very hard character of surrounding limestone, exclude a possible soil-structure interaction issue. The CR0 station is buried (as described for CS0) and CR45 is a borehole seismometer, firmly clamped to the borehole wall. The amplification/deamplification observed on these SSRs are here related to “real” site effects and sensor depth effect. In order to well identify these effects, we performed 1D soil response simulation using the reflectivity method (see Riga et al. 2018 for more information about the used code) and $V_s$ profiles shown in Figure 3. The amplification at high frequencies (up to 5 at 40 Hz) on the CR0/CR3 SSR is mainly due to the weathered limestone zone that affects the 2-3 first meters. Here, empirical and simulated SSRs are in good agreement. The effect of downgoing waves that may induce a deamplification at CR3 likely exists but affects the SSR at higher frequencies (out of the empirical SSR frequency range). However, this downgoing destructive interference is clearly identified on the CR45/CR3 SSR (strong deamplification down to 0.4 at ~13 Hz). Here, the simulated SSR well predict the frequency of the destructive interference. The amplitude is not well reproduced but this is quite common for such very simple simulation approach (that, herein, does not account for not 1-D propagation, incidence angle, lateral heterogeneities, etc.). These few examples demonstrate that the different possible setups of seismological sensors (that are very various in databases) may have a great impact on high frequency content of records. This should absolutely be considered when high frequency analyses are done on such datasets (such as $\kappa$ studies, see e.g. Anderson and Hough 1984).

6. IMPLICATION ON THE KNOWLEDGE OF THE GEOLOGICAL STRUCTURES THAT CAUSE AMPLIFICATION

In this section, we comment how the analysis of SSR may help in the understanding of the exact and detailed geological features (velocity contrasts between different geological formations, velocity gradient within a given geological formation etc.) that produce site amplification. For this, we compared empirical SSRs for both studied sites with simulated SSRs using 1D modelling to explore the different hypotheses formulated at each site (see the description of these hypotheses in section 2 and corresponding differences in terms of velocity profiles in Figure 3).
Figure 8. Left: CS1 (station in shallow man-hole) to CS0 (station buried at shallow depth) mean SSR at Cadarache site. Right: empirical (solid lines) and simulated (dashed lines) SSRs at the rock Cadarache site to highlight the effect of sensor burial depth on the amplification at high frequency.

Figure 9 shows comparisons between empirical and simulated SSRs for the Argostoli site. For both hypotheses, the comparison is quite satisfactory for the AS0/AS83 (surface/downhole) ratio in both the amplitude of maximum of peaks and the resonance frequency (at least for the fundamental and second harmonic). The AS0/AS83 SSRs do not provide clues to select one or the other hypothesis, which is expected because the ratio is independent from the soil layers below 83 m. As for the comparison of AS0/AR0 SSRs (surface/surface), the hypothesis 2, that assumes a “faster” bedrock (and hence a shaper contrast at the basin bottom), produces amplitudes that are more consistent with observations. However, the resonance frequencies are well reproduced for both hypotheses. In order to understand the origin of the frequency shift between the fundamental resonances measured either with surface/surface, or with surface/downhole ratios, we also computed simulated SSRs involving a “virtual” downhole sensor located at the exact position of the basin/limestone interface, that it to say at 91 m for hypothesis 1 (called AS91*) and at 110 m for hypothesis 2 (called AS110*).

For hypothesis 1, there is no significant difference in terms of resonance frequency between AS0/AS83 and AS0/AS91*. Here, for explaining the differences in terms of fundamental frequency between surface/surface and surface/downhole SSRs, we suggest that the significant velocity gradient that characterizes the bedrock velocity profile below the bottom of the basin still contributes to the whole amplification and hence lowers the resonance frequency caused by the basin alone. For hypothesis 2, there is a significant difference in terms of resonance frequency between AS0/AS83 and AS0/AS110*. Here, we suggest that the difference between fundamental frequencies measured with surface/surface and surface/downhole SSRs is mainly explained by the fact that the deepest downhole sensor is significantly shallower than the real basin/limestone interface.

Even if this overall analysis suggests that hypothesis 2 is the most likely, this will still have to be confirmed by the interpretation of recent geophysical measurements (not processed yet) aiming (among other objectives) to better qualify the velocity profile within limestones below the rock surface site (AR0). It is also worth to note that our simulations are just performed for simplified 1D geometry. Figure 10 shows the same comparisons for the Cadarache site. In general, the agreements between empirical and simulated SSRs are much less satisfactory than for the Argostoli site. Indeed, the ratio between basin-depth-to-basin-width is much higher for the Cadarache site than for the Argostoli site and we think that 1D simulation is no more suitable for the Cadarache context. Here again and as expected, the surface/downhole (CS1/CS59) SSR does not allow choosing between the two hypotheses as it is independent of features located below the deepest sensor. However, considering the surface/surface (CS1/CR3) SSRs, the fundamental resonance obtained by simulation using hypothesis 2 produces a more consistent frequency with measurements, although the amplification amplitude does not fit observations. The future analysis should involve 2D and/or 3D simulations.
7. CONCLUSIONS

Through two case studies, performed on Argonet and Cadarache datasets, we compared results obtained by SSR analysis in order to comment the choice of either surface rock reference station or a downhole station situated, if possible, in bedrock below the studied basin. Unsurprisingly, as in most comparison discussions, the final recommendation would be to implement both if the budget allows it. Even if results from the study of only two sites cannot be generalized, our first comment is that placing a downhole sensor in bedrock is not an easy task (even doing abstraction of cost issues), whether because of technical issues (as for Argostoli site) or because of geological interpretation uncertainties (as for Cadarache site). Although more studies should be conducted at both sites to perfectly understand the amplification phenomena, these two case studies illustrate the expected fact that that the use of surface/downhole SSRs alone do not allow to distinguish between interpretation hypotheses as far as remaining uncertainties concern features beneath the deepest downhole sensor.

So, our recommendation is to pursue an installation of a surface reference rock station, even when a vertical array is considered. This method provides the real amplification features at the soil site compare to rock site.

On the other hand, vertical arrays provided evident advantages with respect to surface stations. First,
SSRs computed with downhole stations provided amplification with a lower standard deviation and with a better identification of resonance peaks (if the location of the down-hole stations is close to the main impedance contrast). Second, as far as non-linearity studies are considered (which is definitively the case for Argonet), the vertical array allows a better identification of (even slight) non-linearity features and the exact identification of concerned layers.

Aside the strict discussion about the choice of reference stations, we showed that the procedures for implementing the stations could have a high influence on the high frequency content of the records, and, thus, more care should be taken within the framework of studies that address high-frequency content of ground motion as studies focused on the $\kappa$ parameter.

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9. REFERENCES


