From heterogeneous set of soil data to V_S profile: Application on the French permanent accelerometric network (RAP) sites.

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ABSTRACT:
The French accelerometric network (RAP) provides data for research activities on accelerometric motion in France. The studies, from ground motion attenuation to local site effect evaluations, require a detailed description of the site conditions and then of the site response. A large set of geophysical and geotechnical surveys have been performed in the vicinity of the RAP sites. Considering the heterogeneity of the data at each RAP station and the variability of the shear wave velocity profile ($V_S(z)$) coming from the different surveys, we propose a standard procedure to provide a site characterization. The scope of this procedure is to determine homogeneously an unique $V_S(z)$ and site response parameters at each station, with an index of quality estimate. V_{S30} and EC8 soil classes are then proposed at each site. We find that 64% of the RAP sites are classified as EC8-A, 23% as EC8-B, 10 % as EC8-C and 3% as EC8-E.

Keywords: Accelerometric network, Vs profile, site response.

1. INTRODUCTION

The French permanent accelerometric network (RAP, Pequegnat et al., 2008) consists of 142 free-field stations deployed on the French territory including the overseas territories (French West Indies and New Caledonian island). The stations are managed by 10 sub-networks supervising the stations and depending on the geographical regions: RAP-LGIT in the Northern part of the Alps, RAP-AZUR in the Southern part of the Alps, RAP-BRGM in Eastern Pyrenees range, RAP-OMP in the Western and central part of Pyrenees range, RAP-EOST in the Rhine Grabben region, RAP-OPGC in the central part of France, RAP-LDG in the western region of France, RAP-UBO in the Bretagne region, RAP-IRD in New-Caledonian island and RAP-IPGP in the French West Indies islands. The main objective of RAP is to provide and disseminate accelerometric data recorded in France for research activities such as: the analysis of source mechanisms, the improvement of the regional models of seismic waves propagation (i.e. Ground Motion Prediction Equations GMPE) and the studies of site effects. Knowing a good description of site conditions at each station is crucial information for most of these research activities.

Having urban site instrumentation and site effects as objectives, the RAP instrumentation fell mainly on sedimentary sites. The site response can be either directly obtained from empirical data or computed from soil profile. Thus, several geophysical and geotechnical surveys were performed in the vicinity of the stations, as a supplement to geotechnical and geological description of site already available. Since the installation of the first accelerometric stations started in 1995, these surveys are very heterogeneous from one site to another, due to the improvement in time of the processing methods for site characterization and the techniques available since 1995. The consequences are a large variability of site characterization results in term of $V_S(z)$ profile (see Fig. 1.1).

This paper shows the first step of a larger project, called RAP-ID, led by the CETE Méditerranée and supported by the RAP. The main objective is to define a standard procedure for estimating the site condition at each RAP sites, including all the available information and providing at final an unique shear wave velocity profile ($V_S(z)$) and the site response functions in term of fundamental frequency f_0 and amplification factor. For this reason, we define a standard and homogeneous procedure to determine $V_S(z)$, f_0 and A_0 including an index of quality estimate. The degree of reliability is a parameter reflecting the quality of the survey and the location of the survey to RAP site. The $V_{S}z$ (the average shear wave velocity on the first z meters) for z equal to 5, 10, 20 and 30 meters and the equivalent Eurocode 8 soil classes are determined from the $V_S(z)$.

After presenting the heterogeneity of the data available at each site and the standard procedure applied, we show how the results coming from surveys are interpreted to have a $V_{Sij}(z)$ (for the method j applied at the site i). The procedure to provide an unique $V_{Si}(z)$ at site i from the $V_{Sij}(z)$ is then presented for the case of the OGLP station.

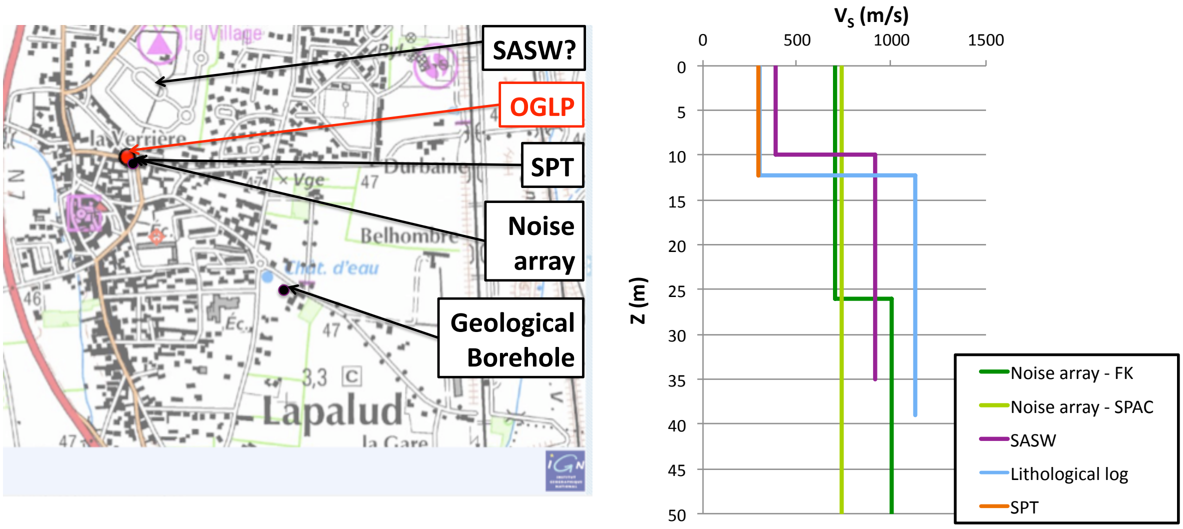


Figure 1.1. Illustration of the $V_{Sij}(z)$ variability for one site extracted from different surveys applied to the OGLP station (RAP-BRGM sub-network).

2. AVAILABLE DATA

Since the beginning of the RAP network, different methods have been locally deployed at each station. We can distinguish invasive and non-invasive methods, providing a direct or indirect estimate of S-wave velocity values. Among the invasive techniques available for our project, we have cross-hole and down-hole profile given a V_S value at several depths, geological boreholes and geotechnical boreholes such as SPT and CPT, for which empirical relationships providing $V_S(z)$ exist (Hasancebi et al.(2007), Jafari et al. (1997)). Non-invasive methods (using both active and passive sources) including spectral analysis of surfaces waves (SASW), multichannel analysis of surfaces waves (MASW) and array noise measurements are also available. The main difference with invasive techniques is these methods give a non-uniqueness of $V_S(z)$ solution by resolving the subsurface structure through inverse problem (Wathelet et al., 2008).

In complement to the methods for site characterization, some methods were employed at each station for defining the site response. Some are based on ground motion recordings (“H/V spectral ratio”, “site/reference spectral ratio” and “inversion method”) and others are based on noise recordings (“H/V spectral ratio”). The “H/V spectral ratio” using seismic noise and the “H/V spectral ratio” using earthquake recordings give access only to f_0 (under some assumptions) that characterize the resonance frequency in presence of strong contrasts (Duval, 2001). The "site/reference" method is the only one identifying quantitatively A_0 (Lebrun et al., 2001). Drouet et al. (2008) determine from the inversion method, robust site responses relative to an average rock-site response, allowing to identify good reference rock sites.

Figure 2.1. shows the distribution of the surveys performed at each sub-network, distinguishing the site characterization methods (a) and the site response methods (b). We can observe the large heterogeneity of the surveys depending on the sub-networks, both in quantity and in type of methods applied. These heterogeneities can be due to, the installation date of the first station and the experience of institutes in charge on site characterization and site response analysis. The geological boreholes are the only data represented in the whole sub-networks and provided by the on-line geological boreholes database for France (http://infoterre.brgm.fr). For RAP-Azur sub-network, the site response methods are more developed than the site characterization methods.

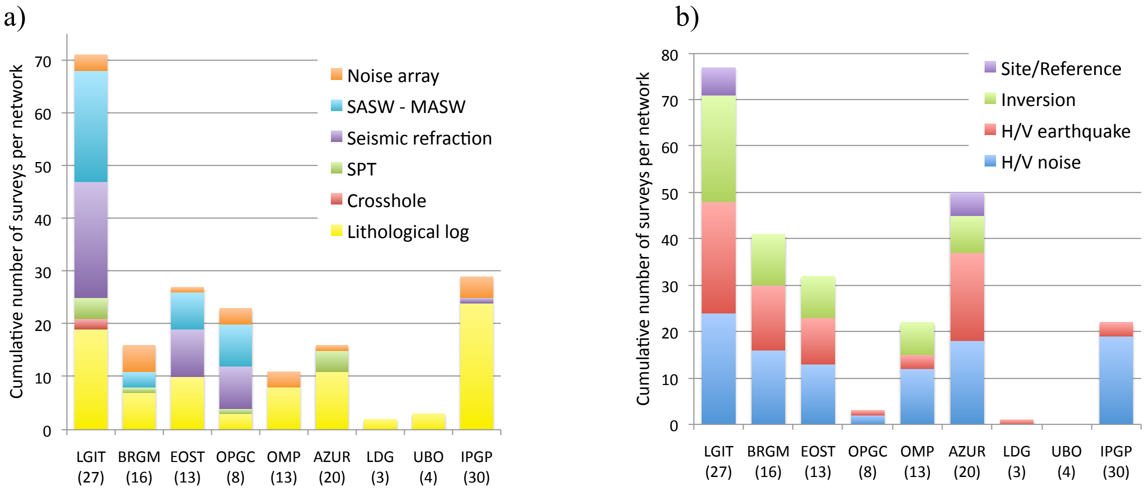


Figure 2.1. Histogram showing for each RAP sub-network the cumulative number of surveys deployed to obtain both the soil parameters and the site response parameters. The number under the sub-network name corresponds to the number of station managed by sub-network and so at the maximal height of the part of the bars of the histogram.

3. FROM THE SITE CHARACTERIZATION METHODS TO $V_{SIJ}(Z)$

Most of the site characterization methods do not give directly an unique $V_S(z)$. The purpose of this section is to illustrate how the results of the method (j) applied at the site (i) are used to determine an unique velocity profile ($V_{Sij}(z)$) from the surface to the seismic substratum:

- From geological borehole to $V_S(z)$: Lavergne (1986) proposed an empirical estimate of ranges of V_S values for ground types. From the geological borehole, an approximate $V_{Sij}(z)$ can be calculated. In this paper, we choose the mean value of V_S interval. The depth interfaces are well constrained whereas the Vs is approximated.

- From Standard Penetration Test to $V_S(z)$: Many authors attempted to define empirical relations to estimate V_S from the penetration resistance (N). We chose to use 19 empirical relations established for “all ground type” (Hamza et al, 2007, Hanumantharao et al 2008, Hasancebi et al, 2007, Jafari et al 1997). The median of the 19 velocity profiles coming from the empirical methods is calculated. This median profile is simplified in homogeneous layers. The $V_{Sij}(z)$ is obtained by calculating the harmonic mean of the median velocities on homogeneous layers.

- From seismic refraction to $V_S(z)$: Seismic refraction gives V_S in 2 space-dimensions (V_S profile at the center and extremity of the measurement line). The $V_{Sij}(z)$ is given by the velocity profile in the middle of the profile (directly from the S-waves or from the P-waves by taking a constant Poisson’s ratio of 0.25 ($V_S=V_P/(3^{1/2})$).

- From the inverse methods (SASW – MASW – Array noise) to $V_S(z)$: The SASW, MASW and array noise methods provide infinity of velocity profiles with different misfit values (sum of the difference between the dispersal curve of the proposed solution and initially pointed) (Wathelet et al., 2008). We choose to select an envelope of $V_S(z)$ corresponding to the profiles with a misfit lower than 0.02. The $V_{Sij}(z)$ is determined by taking the median profile of this envelope.

- From the site response to $V_S(z)$: The shape of the site response can also give information about $V_S(z)$. For the purpose of this research, we consider that: 1) When the curve is flat, the site is not prone to site effect. The $V_S(z)$ is modeled by a half space. 2) When the curve discloses a clear peak with amplitude up to 2, the site is prone to site effect. The $V_s(z)$ has at least one interface. In this case, there is a simple relation between the resonance frequency (f_0), the thickness of the sediment (H) and the shear wave velocity (V_S) of the topmost layers: $f_0=V_S/4H$ (assuming a 1-D soil model). This relation can be used to have an estimation of H or Vs when one of both parameters is known as well as f_0.

4. PROCEDURE

As aforementioned, the quantity and quality of the surveys are heterogeneous at each site. Some sites, used as test site (for example the Montbonnot borehole in the Grenoble basin, station OGFH, OGFB and OGFM are fully described (Guéguen et al. (2007)), whereas some others are poorly investigated. Besides, different groups with different scopes, equipments and treatment tools, performed the investigations from their own initiative. Thus, a standard procedure must be proposed to integrate this wide heterogeneity and define a standard stair-shape velocity profile at each station.

At a given site, the $Vs_{ij}(z)$ or the site response can be variable from one survey to another. To define a standard procedure, 3 standard gradings of the methods, according to their relevancy and accuracy in giving the VSij(z) as well as f0 and A0, are defined. 1) The site characterization methods are sorted according to their ability to give the depth of boundaries between two homogeneous layers (Grading-1). In our study, we give priority to invasive methods against non-invasive methods (SPT, geological boreholes, cross-hole, seismic refraction, SASW, MASW, noise array methods, from f0 corresponding to the more to less accurate methods, respectively). 2) The site characterization methods are sorted according to their capacity of giving the V_S of the layers (Grading-2). From a synthesis of existing data, Moss et al. (2009) defined coefficients of variation for shear wave velocity measurements according to the methods used. Cross-hole and down-hole methods are on the order of 1-3%, SASW 5-6% and correlation between Vs and geologic units, 20-35%. Thus, we give priority to cross-hole and SPT rather than, seismic refraction, SASW, MASW, noise array methods and finally correlation with geological units. 3) The site response methods are sorted according to their ability to give f0 and A0. In this project, we give priority to the methods based on earthquake recordings (Site/reference, H/V earthquake, inversion), rather than the methods based on seismic noise (H/V seismic noise).

Such gradings are very sensitive and are proposed in the framework of this project only. These standard gradings are modulated, in each site, as function of the quality of the surveys (measurements and process). The procedure for a given site i is as follows:

1. Evaluation of the quality of the site characterization methods at site i. The quality is a 5 degrees scale (vh, h, m, l, vl, from the very high to the very low quality, respectively) and is defined according to: the distance of the investigation to the RAP site, the adequacy between the geomorphologic context of the site i and the location of the survey, and the quality of the deployment of the method and the data processing (table 4.1). For the last point, we refer to the investigation report provided by the operator, when available. In the case of normative methods, such as SPT, the quality of the method deployment and data processing is by default chosen to "high". The maximal depth of investigation for each survey is also calculated.

2. Evaluation of the quality of the site response methods at site i according to the quantity of input data used. The number of earthquakes or number and length of stationary noise windows are the two main criteria. The site response curves are interpreted to determine the existence or not of site effects. If there are site effects, the site response parameters f_0 and A_0 are evaluated.

3. The site specific gradings of the surveys j at site i (Grading-1_i, Grading-2_i) are realized by modulating the standard grading according to the quality of the surveys evaluated in the first step. The modulation is performed by permuting the rank of two methods if the inferior method has two quality degrees more than the previous one.

4. The final $V_{Si}(z)$ is constructed using all data according to their rank in the gradings (1 and 2), fallowing these two steps: a) The depth of the boundaries ($H_1 \ldots H_k$) are deduced from the highest quality survey of the grading-1_i. The V_S in the layers ($Vs_1 \ldots Vs_{k+1}$) are given by the highest quality survey of the grading-2_i. In case of this survey does not provide the deepest investigation, we select the immediately lower quality method to find the Vs of the deepest layers. b) To complete the shear wave profile two conditions are required: 1) a Grading-1_i method indicates a deep boundary, even if this method has a low quality level. 2) the S-wave velocity profile for the two grading-1_i methods (high and low quality) for the uppermost layers must have the same order of magnitude.

5. Evaluation of the quality of the final shear wave velocity. The quality of the S-wave velocity at the different depth depends on the quality method used and the variability of the S-wave velocity from one method to another. At this stage, we attribute a quality index of S-wave velocity for each layer.

6. Calculation of the mean shear wave velocity for the 5, 10, 20 and 30 first meters (V_{S5}, V_{S10}, V_{S20} and V_{S30}) and determination of the EC8 soil class. Their quality index are given by the quality affected to the S-wave velocity in each layer. However, when the V_{S30} is larger than 800 m/s, the quality attributed to the soil class EC8-A can be high, even if the velocity is not well constrained.

Tableau 4.1: Quality of the site characterization surveys.

Location of the survey Deployment of the method Quality data processing Quality	0 m	Distance < 500m and same geomorphologic context	Distance < 1000m and same geomorphologic context	Unkown/ Different
high	**Vh**	**h**	**m**	**l**
medium	**h**	**m**	**l**	**vl**
Low	**l**	**vl**	**vl**	**vl**

4. APPLICATION OF THE PROCEDURE

To illustrate the procedure, we applied it to the station OGLP (figure 1.1). In this site, several site characterization methods were performed (Table 4.2) leading to different shear wave velocity profiles (figure 1.1). In the table 4.2, the quality of the surveys is determined according to the step one of the procedure.

At OGLP, only ambient vibrations measurements were performed to get f_0. The analysis of the ambient vibration was performed using horizontal to vertical spectral ratio. From this analysis we find that site effects at this station may exist and the resonance frequency is close to 0.6 Hz.

The site characterization surveys were sorted according to step 3 (table 4.3 and table 4.4). A first boundary in depth is given by the SPT at 12 meters. Table 4.3 indicates the velocity of the first two layers. The velocity of the first layer is given by the SPT, the second by the SASW.

Table 4.2:First step of the procedure for the station OGLP:

Investigations performed at OGLP	Depth validity (m)	Precision of the application and treatment of the method	Distance to the RAP site (m)	adequacy between the geomorphologic context	Quality degree
SPT	12	h (by default)	42	Yes	h
Geological borehole	40	h (from author survey report)	605	Yes	m
SASW	35	m (from author survey report)	?	Yes	l
Noise array	50	vl (from author survey report)	0	Yes	vl

The low frequency peak of the H/V using seismic noise indicates a deeper second interface. Indeed, the resonance at 0.6 Hz cannot be related to the first interface using the $f_0=V_{S1}/4H$ relationship. The shear wave velocity profile must be composed of at least three homogeneous layers. From f_0, V_S in the layer 1 and V_S in the layer 2, we estimate the depth of the second interface (350 m) using a harmonic mean following the equation 2. None of the surveys give the velocity of the last layer; we can just infer that the velocity is higher than the one of the second layer.

$$.1)\, H_2 = V_{S2}\left(\frac{1}{4f_0} - \frac{H_1}{V_{S1}}\right)$$

Table 4.3: Third step of the procedure for the station OGLP

Grading of the studies according to H.	Depth validity (m)	Depth interface 1 (m)	Depth interface 2 (m)
SPT	12	**12**	-
Geological boreholes	40	14	-
SASW	35	10	-
Noise array	50	26	-
f_0 from ambiant vibration H/V	-	-	**Low frequency peak (0.6 Hz)**

Table 4.4: Fourth step of the procedure for the station OGLP

Grading of the studies according to V_S	Depth validity (m)	Vs of the layer 1 (m/s)	Vs of the layer 2 (m/s)	Vs of the layer 3 (m/s)
SPT	12	**290**	-	-
SASW	35	385	**910**	-
Noise array	50	780	780	-
Geological boreholes	40	300	1500	-

The final shear wave velocity profile and the associated reliability degree are illustrated in the table 4.5. The $V_{S5,\,10,\,20\;30}$ and EC8 soil class are calculated as well as the associated reliability and illustrated in the table 4.6.

Table 4.5 : Fifth step of the procedure for the station OGLP

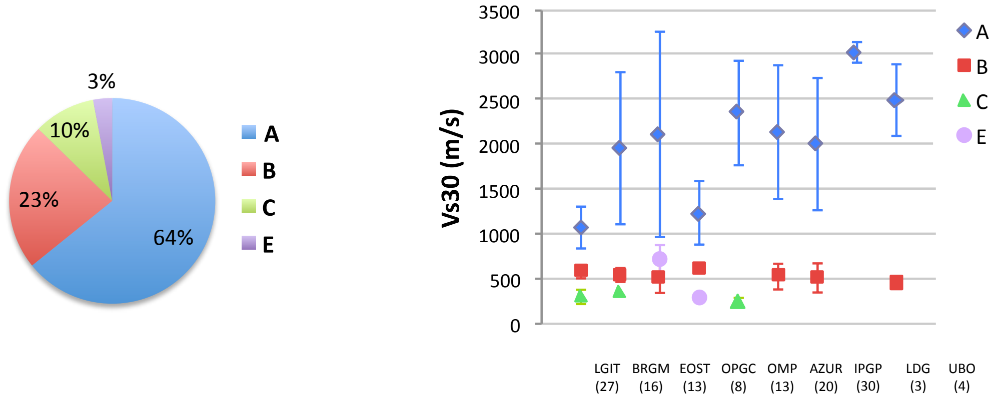
	Depth (m)	Vs (m/s)	Reliability
Layer 1	0-12	290	h
Layer 2	12-350	910	l
Layer 3	>350	>910	vl

Table 4.6 : Sixth step of the procedure for the station OGLP

		Reliability
Vs5 (m/s)	290	h
Vs10 (m/s)	290	h
Vs20 (m/s)	400	l
Vs30 (m/s)	490	l
EC8 class	B	l

5. DISCUSSIONS

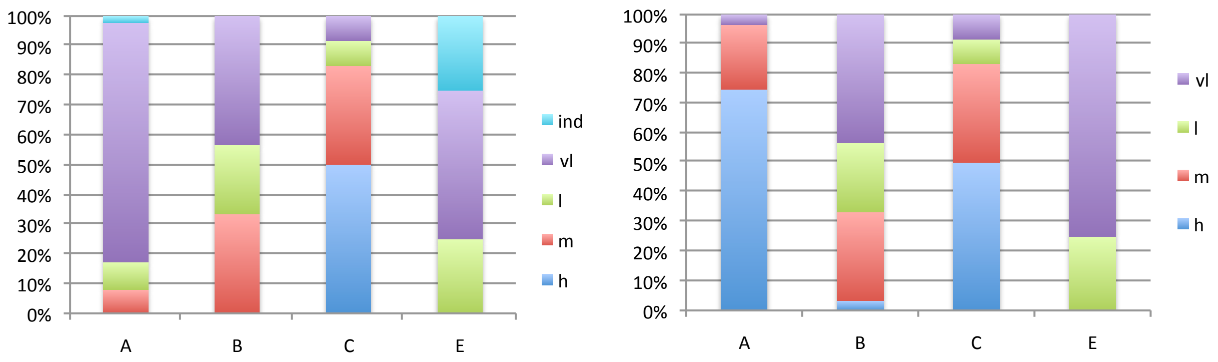
The procedure was applied on the whole network. Thus, the V_{S30} and the EC8 soil classes were determined. The figure 5.1.(a) shows the EC8 soil distribution of the RAP sites. The majority of the sites are rock sites (EC8-A, 64%). Among the sedimentary sites, the EC8-B class is the most represented with 23%, followed by the soil class EC8-C (10%), EC8-D is not represented and only 3% of the sites were classified in EC8-E. The figure 5.1 (b) indicates the average V_{S30} and standard deviation by sub-networks and by EC8 soil classes. For example, for the RAP-LGIT and RAP-OPGC sub-networks, the V_{S30} at EC8-A site is well constrained, which can be attributed to the availability of SASW and refraction surveys. For the rest of the sub-networks, the V_{S30} is not well constrained because generally evaluated using the geological boreholes.



a)

b)

Figure 5.1. a) EC8 soil class distribution on the whole network and b) mean V_{S30} and standard deviation according to the EC8 soil classes for each sub-network.



a)

b)

Figure 5.2. Degree of reliability attributed to a) the Vs30 and b) the EC8 soil classes for the different

soil classes.

The quality degree of the V_{S30} and the EC8 soil class is highly dependent on the EC8 soil class attributed to the site. In the cases of rock sites, more than 80 % of the sites have very low quality degree for V_{S30} whereas the EC8 soil class was well known. It is explained by the criteria followed in our procedure. Even if the V_{S30} is not well constrained for rock sites, it is up to 800 m/s which indicates for sure an EC8-A site. For the sedimentary sites, the quality of EC8 soil classes and V_{S30} are related which implies a certain similarity between the two results. Besides, the quality of V_{S30} in sedimentary sites is generally higher than the quality at rock sites because more surveys were performed and the methods applied are more adapted for such sites.

6. CONCLUSION

In this article, we present a standard procedure for defining an unique stair-shape shear wave velocity profile from a set of site characterization surveys. This procedure was made to 1) define homogeneously an unique $V_S(z)$ by station on the whole network and 2) define the $V_S(z)$ in as described as possible manner. In addition, this work syntheses the available data and associated reliability on RAP sites to anticipate future investigations on the network.

The next steps of this project are to find the regional seismic hazard under each RAP station by using the $V_{Si}(z)$ to compute the site response at each RAP_i site and to compare it with the empirical site response already performed with earthquake data.

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