

INSTALLATION OF A BOREHOLE VERTICAL ARRAY IN THE VAR VALLEY, NICE,

Nathalie DUFOUR¹, Jean-Baptiste PAYEUR², Etienne BERTRAND², Diego MERCERAT², Julie REGNIER², Vincent VANCRAENENBROECK³, Morgan ALLIAUME³, Frédéric CAPELLE³, Philippe LANGLAUDE², Michel PERNOUD², Hélène CALISSANO¹, Laurent BATILLIOT¹, Marlène COUDERT¹

ABSTRACT

Because of its geodynamic context, its extreme geography (transition from a deep basin to high mountains in less than 80 km), its concentration of stakes (human, urban centers, economic), combining to the increase of the coastal population density, the french Riviera forms an ideal laboratory to study natural hazards and risks. This is particularly true for seismic risk since the area is prone to the highest level of seismic activity in France's mainland.

One of the main component of seismic hazard assessment is related to lithological site effect due to soft layers overlaying hard bedrock encountered for example in the Alpine valleys. The quantitative assessment of the ground motion effects associated with the local surface geology, is thus a major issue in seismic hazard and engineering seismology studies. Frequency dependent site amplifications are known to be mainly caused by reverberations and resonance effects of S-waves within the unconsolidated sediments that are found in fluvial basin for instance. To better understand these site effects it seems interesting to record the interaction of the seismic waves with the soil materials by setting up verticals seismological arrays.

Within the framework of the PORTE project, supported by the PACA region and the European ERDF funds, one of the objectives of which is to create a technical and innovation platform dedicated to environmental observation in order to obtain long-term recordings in-between and during crisis. We propose the establishment of a vertical seismological network in the lower Var valley in Nice. The valley is less than 1 km width but previous geophysical and geotechnical studies have shown that the bedrock depth could locally reach 150 m. We started by carrying out in-situ and laboratory measurements to characterize the future site of implantation. The geophysical measurements (MASW and AVA) allowed us to define a S-wave velocity profile while the laboratory measurements on core drillings samples informed us on the mechanical behaviour of the different sedimentary layers. Other in situ characterisation (pressimeters) coming from the literature were also used. On the studied site, the bedrock (Pliocene marl) is found close to 30 meters depth, the shear wave velocity measurements result in a V_{s30} close to 370 m/s and the associated fundamental resonance frequency, derived from H/V spectral ratio on ambient vibration, is found at around 2.5 Hz. The soil column is mainly composed of saturated sandy layers including pebbles and gravels. In a few months, an instrumentation combining accelerometric and velocimetric sensors will be set up at three depths (surface, -10 m and -31 m) and will continuously record the seismicity of the area. This instrumentation will be complemented by interstitial pressure measurements that will allow to record its variation related to different cyclic solicitations.

Borehole vertical arrays; Geophysical measurements; Laboratory tests

¹ Project-team MOUVGS, Cerema, Aix-en-Provence, France, nathalie.dufour@cerema.fr

² Project-team MOUVGS, Cerema, Sophia Antipolis, France

³ Cerema, Saint Quentin, France

1. INTRODUCTION

According to Zeghal et Elgamal (2000), the dynamic characteristics of ground response are being increasingly documented through a growing set of worldwide sites instrumented with vertical downhole seismic arrays. In the United States, an early down-hole data set was recorded at Union Bay in Seattle, Washington. This data was employed to check site amplification procedures, and analyze the response of peat and clay deposits in Seattle. In Japan, an array of two surface and two downhole seismometers was installed on the premises of Tokyo Station in the late 1950's. Using these earthquake records, site resonance and damping characteristics were estimated. These early efforts were followed by more complete array installations, such as at Chiba, Lotung, Hualien, Port Island, and Treasure Island sites. Since the 1980's, data from downhole seismic arrays that include pore-pressure piezometers became increasingly available (Wildlife Refuge and Lotung sites for example). Such data sets offer a more complete picture of site response.

These past experiences showed that downhole vertical-array records offer a valuable source for evaluating site seismic shear stress-strain histories, assessing the mechanisms of site amplification, stiffness degradation and liquefaction, and calibrating constitutive models and computational modeling procedures (Zeghal et Elgamal, 2000).

In France, only two sites have been equipped with sensors (Guéguen et al. 2015) :

- (1) Montbonnot borehole close to Grenoble : since 2000, the Montbonnot borehole is equipped with nine accelerometer acquisition points distributed between the free surface and the bottom of the sedimentary fill in the Grenoble valley, at around 535 m depth,
- (2) Belleplaine borehole in Guadeloupe Island (French Antilles): since 2007, the borehole in Belle-Plaine is equipped with three accelerometer acquisition points distributed between the free surface and the bottom of the coastal fill at around 39 m. Four pressure sensors complete the set-up (Bonilla et al, 2017)

Within the framework of the PORTE project, supported by the PACA region and the European ERDF funds, a third vertical seismological network will be installed in Nice, in the lower Var valley. It will be part of a technical and innovation platform dedicated to environmental observation in order to obtain long-term recordings in-between and during crisis. This system will be presented in this article.

2. PRESENTATION OF THE BOREHOLE SITE

2.1 Location

The vertical array will be located in the lower Var valley in Nice, Alpes Maritimes, one of the most important seismic zone in metropolitan France (see Figure 1). The future station consists in two vertical arrays of sensors. For the moment, two boreholes corresponding to the future arrays have been drilled, in order to locally investigate the geotechnical conditions and to enable the installation of downhole sensors.

2.2 The lower Var valley geology

The Var river delta is an alluvial area with soft soil surrounded by thick formations of Pliocene conglomerate, and older marly limestones. The alluvial plain of the Var consists of several tens of metres of coarse alluvium with great sandy and gravelly lenses. Geotechnical surveys have been carried out to characterize the zone (e.g. Dubar, 2003). The quaternary sediment thickness has been estimated between 40 and 60 meters over a pliocene conglomerate considered as bedrock. The average value of S-wave velocity in the upper 30 m of the soil profile is estimated as $v_{s,30} = 235$ m/s, which corresponds to a soil type C, according to Eurocode 8 (European Committee for Standardisation, 2004). The water table is rather shallow and the valley is one of the main aquifer of the area.

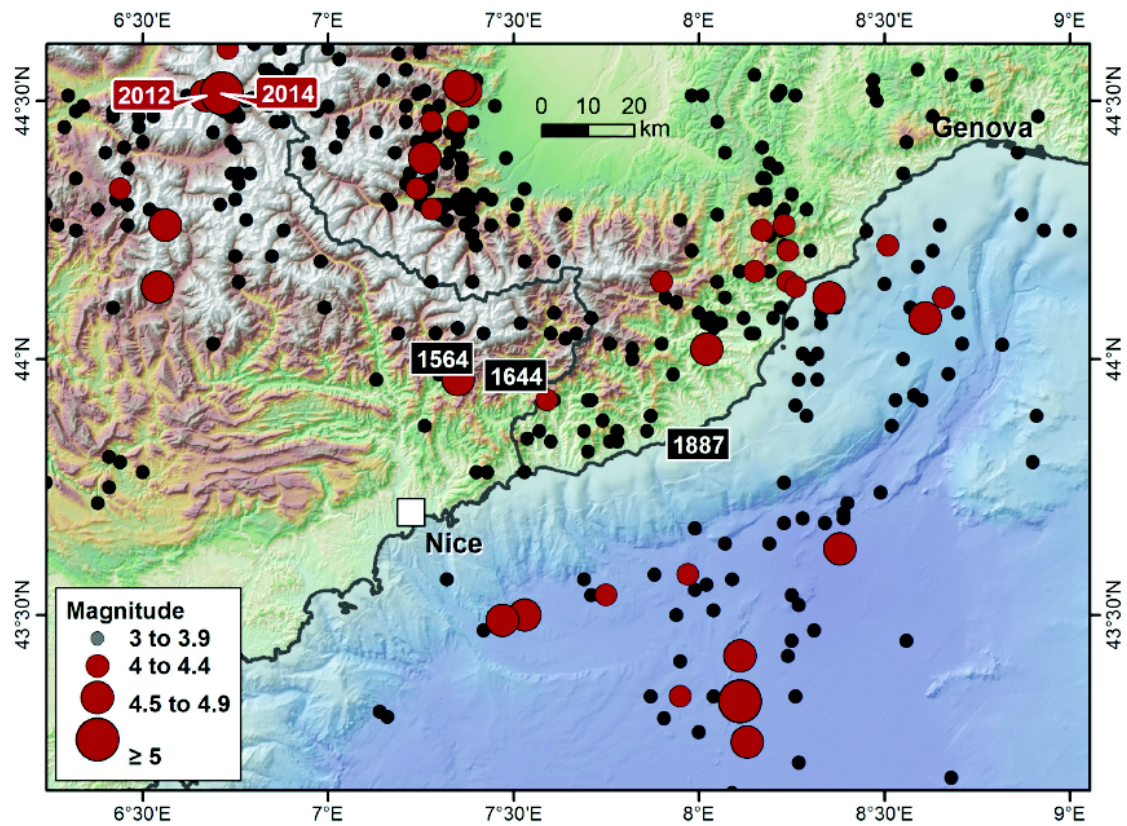


Figure 1. Regional instrumental seismicity from BCSF catalog (1960-2015). Nice city shown by a white square. Two main Barcelonnnette events of 2012 and 2014 are shown in the upper-left area and three reference historical events located by black rectangles. (GEOAZUR)

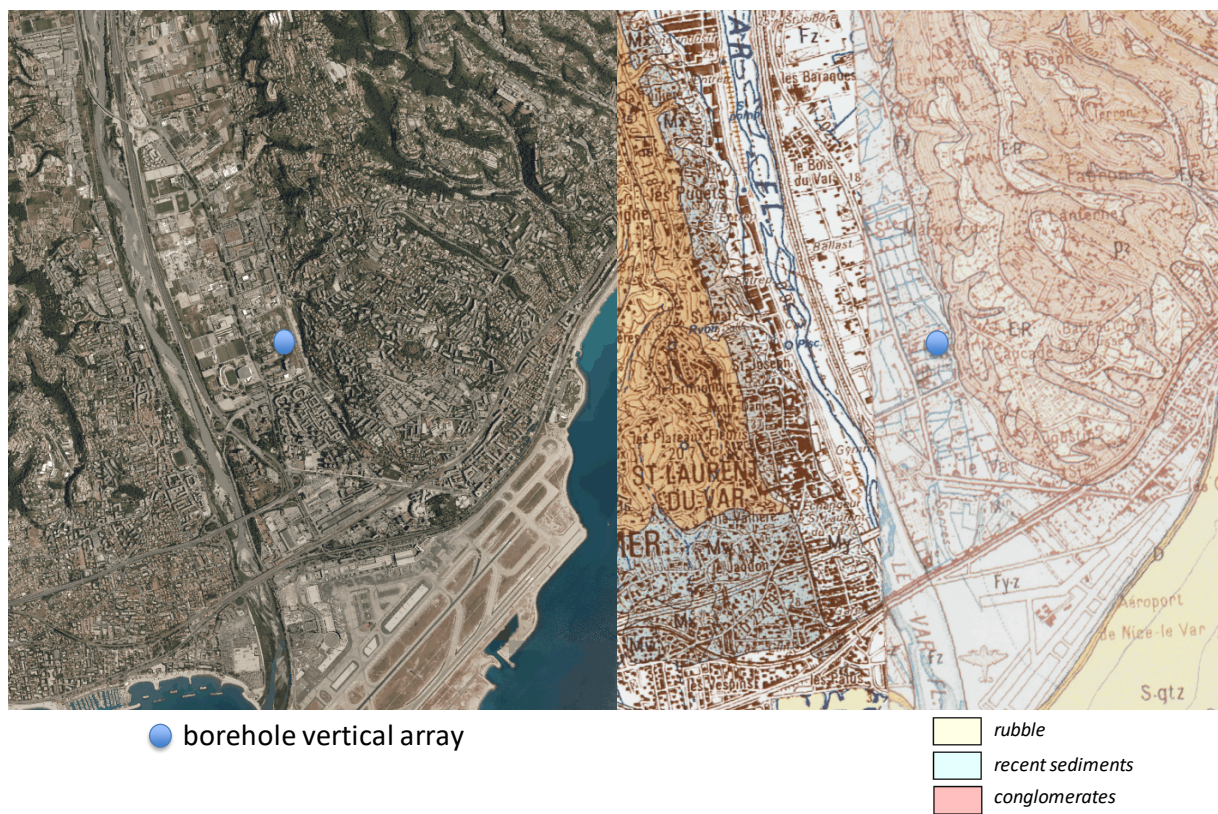


Figure 2. The future Nice borehole test site : satellite image on the left side and geological map on the right side

3. SITE INVESTIGATIONS

Geotechnical and geophysical investigations were carried out to define the subsoil structure at the borehole site.

3.1 Description of the soil structure

Two boreholes were drilled in Nice at the locations of two vertical arrays to investigate geotechnical conditions and to enable the installation of downhole sensors. The maximum depths of exploration were 10 m and 31 m. The soil profile is described in Table 2. Measured values of unit weight and water content are also given in table 2 and Figure 3.

Table 1. Soil description from the top surface.

Soil	Depth (m)	Description
Sand and rubble	0.0– 12.5	Very heterogeneous layer as illustrated in Figure 3, which contains recent Var sediments from clean sand to rubble characterized by a maximum diameter of 120 mm.
Silt - Organic clay	12.5- 17.5	Sandy silt and organic silty clay which contains wood elements.
Sand and rubble	17.5- 28.5	Very heterogeneous layer which contains recent Var sediments from sand to rubble characterized by a maximum diameter of 100 mm.

Table 2. Soil profile from the top surface, unit weight and water content.

Soil	Depth (m)	Thickness (m)	Unit weight γ (kN/m ³)	Water content w (%)
Sand and rubble	0.0– 12.5	12.5	$13.9 \leq \gamma \leq 25.8$	$6.0 \leq w \leq 12.7$
Silt - Organic clay	12.5- 17.5	5.0	$17.4 \leq \gamma \leq 20.1$	10.5
Sand and rubble	17.5- 28.5	11.0	22.5	-

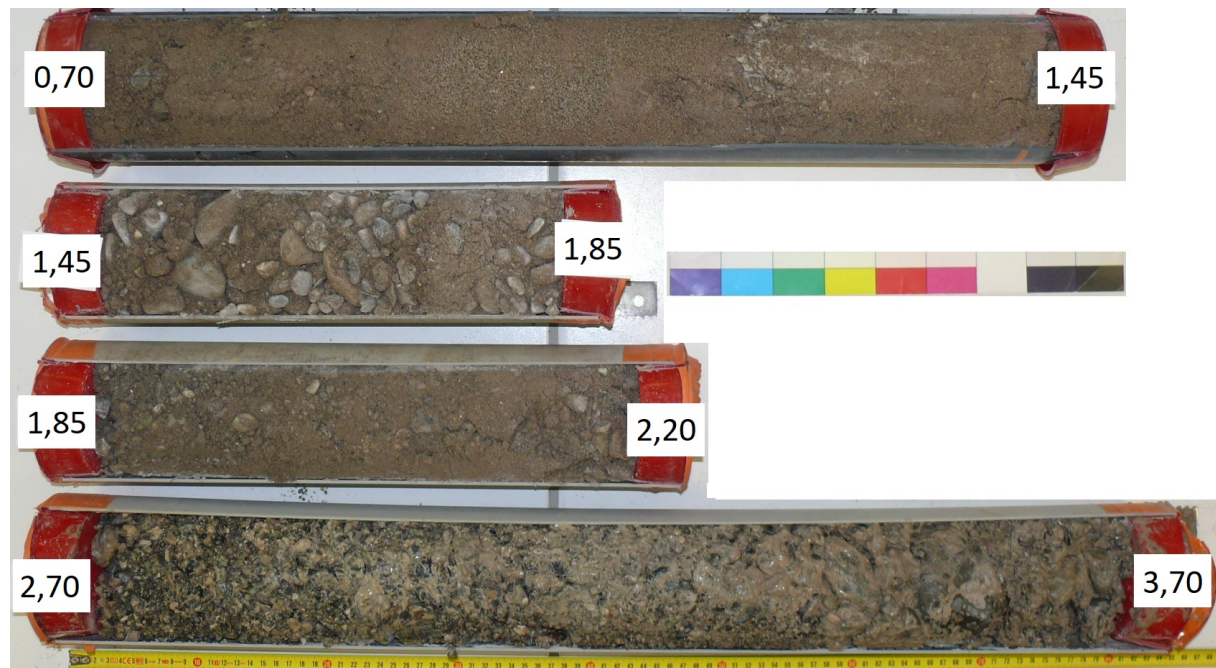


Figure 3. Samples from 0.70 to 3.70 m depth

3.2 In-situ tests

Some Pressure Meter Tests (PMT) have been carried out within the investigated area (Fondasol, 2016). Those PMT (SP1, SP2 and SP3 shown in Figure 7) tests have been done in three open boreholes, 20m depth each, following the NF EN ISO 22476-4 nom. 24 PMT have been performed in the upper layers of soil and can be related to the first sand and rubble layer; 8 PMT can be related to the silt- organic clay profile and 5 to the upper part of the second sand and rubble layer. The pressiometric values E_m (pressiometric modulus) and pl^* (net limit pressure) related to the site soil layers are given in Table 2.

Table 2 : Pressiometric values for each soil profile

Soil	E_{m_min} (MPa)	E_{m_mean} (MPa)	E_{m_max} (MPa)	pl^*_{min} (MPa)	pl^*_{mean} (MPa)	pl^*_{max} (MPa)
Sand and rubble	1.7	7.8	370	0.2	1.7	4.9
Silt -Organic clay	0.8	3.8	12.9	0.1	0.7	2.3
Sand and rubble*	11.8	19.9	34.7	1.1	2.1	2.9

* in its upper part only

Parameters resulting from Pressure Meter Tests highlight an important heterogeneity within the first sand and rubble layer, due to the local variability of soil profile (silt – sand – gravel), while the silt-organic clay profile presents a relatively homogeneous set of PMT parameters. The comparison of those parameters, with soil water content and unit weight along the depth is also given in figure 4.

Two permeability Lefranc tests (NFP 94-132 norm) have also been performed in a borehole, at depths 2.5 m and 5.5 m.

These tests indicates a soil permeability around 10^{-6} m/s for the first sand and rubble layer, which is relatively small for this kind of soil and can be linked with silt inclusions within this layer.

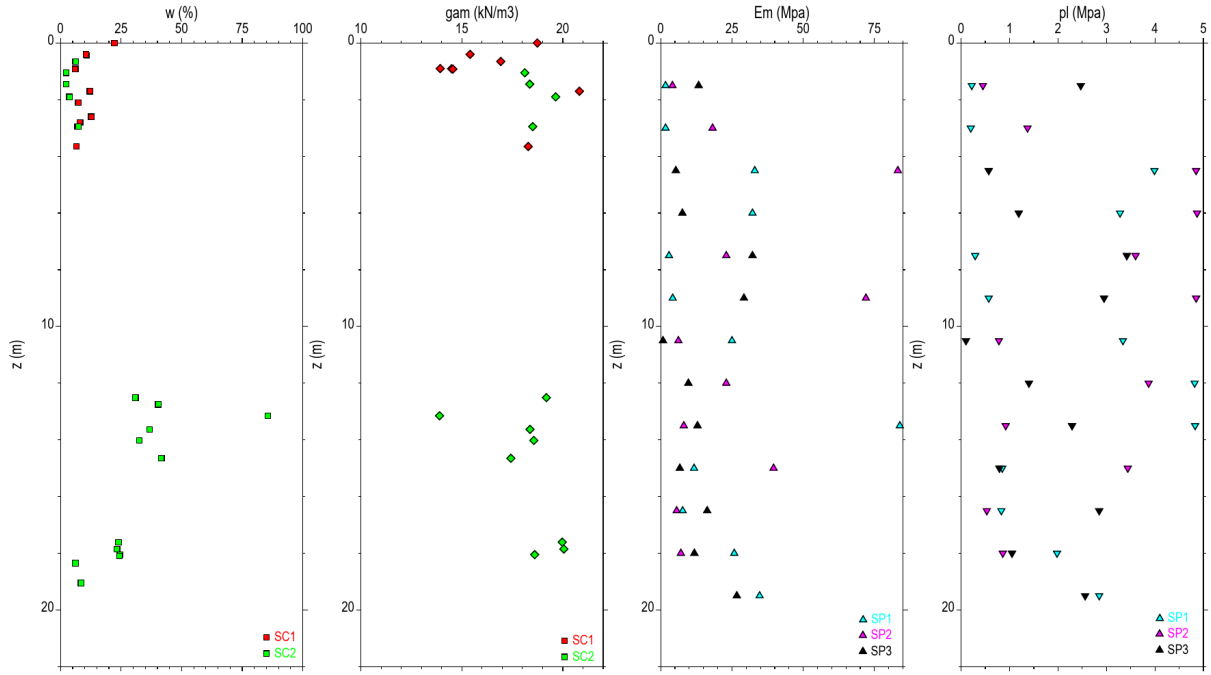


Figure 4. From left to right : Water content, unit weight, pressiometric modulus and net limit pressure versus depth

3.3 Laboratory tests

Soil samples were retrieved from boreholes SC1 and SC2. Cyclic triaxial laboratory testings were performed on specimens carved from those samples in order to identify the dynamic properties of different types of soil (see Table 1). Three samples were tested : two samples are remodeled sand (0.8 m depth) and one anther is silty sand (20,0 m depth). The test consists in applying several successive sequences of undrained cycles in a range of axial deformations between 10^{-4} and 10^{-2} . An example of non linear relationship between deviatoric stress $q = \sigma'_a - \sigma'_p$, (where σ'_a and σ'_p are the axial and radial stresses) and axial deformation, obtained from a triaxial testing on a sandy sample located at 0,8 m depth, is presented in Figure 5.

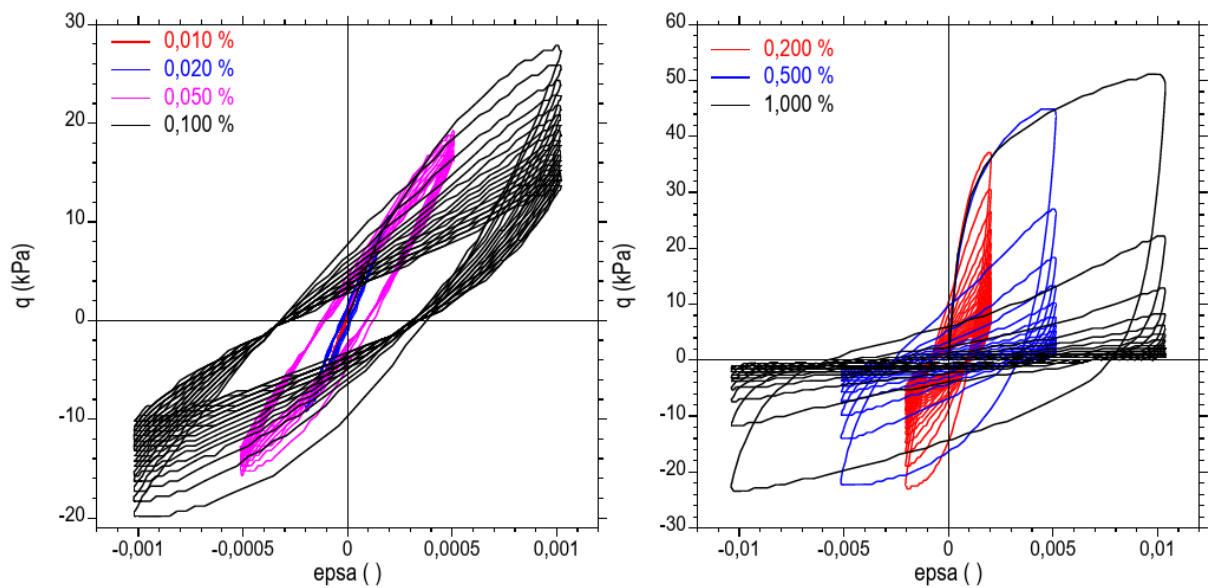


Figure 5. Relationships between deviatoric stress q and shear strain ϵ_{psa} – Several successive sequences of undrained cycles in a range of axial deformation : 0,010 % - 0,020 % - 0,050 % - 0,100 % - 0,200 % - 0,50 % -

1,000 % on a sample located at 0,80 m depth

Following (Serratrice, 2016), Fourier's serial approximation of the experimental records allows the precise identification of secant Young modulus E_t and hysteretic damping ratio D . Relationships between secant modulus and shear strain (epsaDA) and between hysteretic damping ratio and shear strain are plotted in Figure 6.

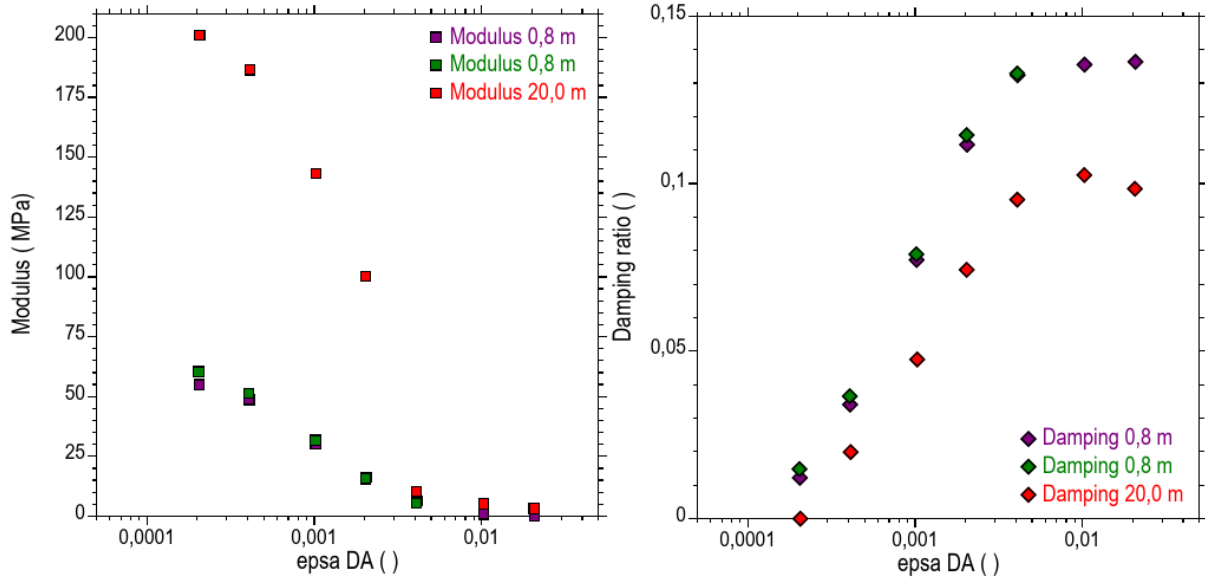


Figure 6. Left : Relationships between secant modulus and shear strain –Right : Relationships between hysteretic damping ratio and shear strain

3.4 Geophysical measurements

Two campaigns of seismic data acquisition have been carried out at the site near boreholes SC1 and SC2. The first one consisted ambient noise arrays of 11 velocimetric stations (Le3D 5sec) set up in two circular concentric arrays of 5 m - 20 m and 20 m - 50 m radius (see Figure 7) recording during an hour with a sampling frequency of 150 Hz. The second seismic campaign consisted in a classical MASW profile with a linear array of 24 geophones (corner frequency of 4.5 Hz) with inter-geophone distances of 1.5 m (total length of 34.5 m) and 3 m (total array length of 69 m) and a sampling frequency of 500 Hz. A sledgehammer of 10 kg has been used as seismic source. The recovered frequency band combining both techniques goes from 1 Hz to 40 Hz allowing for a detailed inversion of the dispersion data to evaluate the position of the bedrock (considered here as the consolidated conglomerates of the nearby Nice hills with shear wave velocities around 1200 m/s) and to characterize seismic velocities of the infill basin material.

Data processing has been done using the Geopsy software package (Wathelet et al, 2008). The passive array data has been analyzed by SPAC and FK techniques for lower (< 5Hz) and moderate (5 – 15 Hz) frequencies, respectively. Classical linear FK analysis is used to for the MASW active profiles. The inversion is done by a non-linear nearest neighborhood approach (Wathelet et al., 2008) with the constraint of fitting the clear H/V resonant pick measured on the site at 2.5 Hz. After several attempts, we decide to fix the soil column parameterization to three homogeneous layers which gives a satisfactory fit to the dispersion data. The preferred soil column (see Figure 8), using just geophysical data, consists of a layer of 3 to 4 m of rather unconsolidated material with V_s around 250 m/s, followed by a thick layer of gravel and sandy material ($V_s \sim 380$ m/s) down to 30 - 35 m depth where the bedrock ($V_s \sim 1200$ m/s) is found.

One step further, taking into account the geotechnical and geological characterization of soil samples from both SC1, SC2, SP1, SP2 and SP3 boreholes (Tables 1,2 and 3), we constraint the inversion

method to allow for a seismic velocity inversion (i.e. *low-velocity* layer) in between 10 m to 15 m depth that could correspond to the Silt - Organic clay material revealed from the borehole samples. The new model, allowing the velocity inversion, also fits the dispersion data satisfactorily and therefore can be used as the preferred model for the site. It consists of the shallow unconsolidated layer with V_s around 250 m/s down to 3 - 4 m depth, followed by a thick layer of gravel and sandy material ($V_s \sim 420$ m/s), intercalated by a 5 m thick low velocity layer with a $V_s \sim 350$ m/s, down to 35 - 45 m depth where the bedrock is found. It can be mention that the uncertainty in the bedrock depth increases relative to the previous three layers model (see Figure 9).



Figure 7. Position of the stations of the seismic array (triangles) and the MASW profile. Boreholes SC1 and SC2, where accelerometers will be installed, are shown by orange and green diamonds. Geotechnical boreholes SP1, SP2 and SP3 by yellow, blue and red diamonds

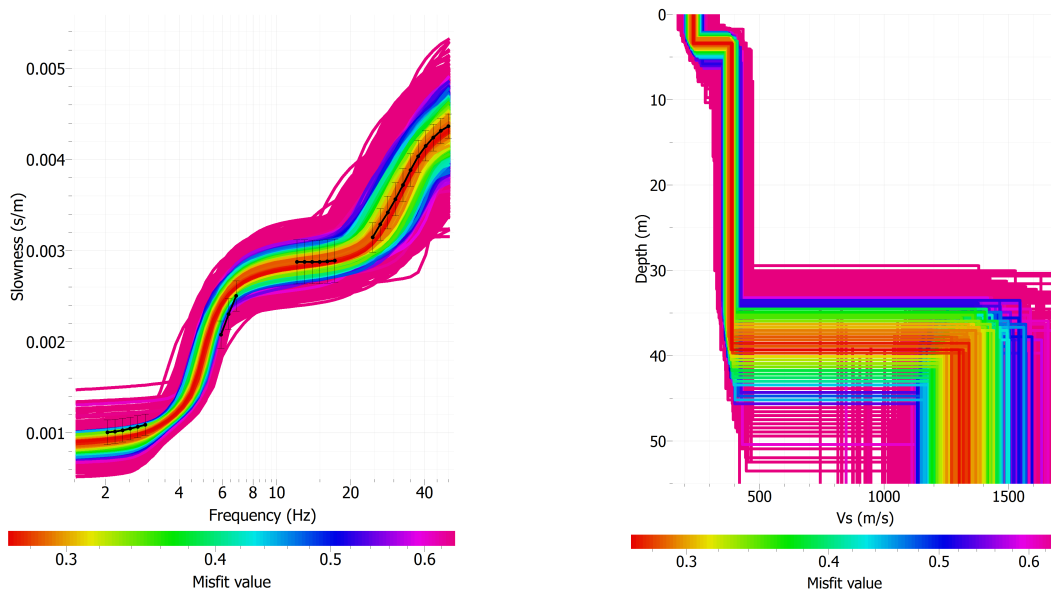


Figure 8. Left: Measured dispersion curve for the site (black dots) with calculated dispersion curves for each model (color scale depending on the misfit level). Right: Vs velocity models with satisfactory misfit values (< 0.6). Parameterization by three homogeneous layers corresponding to silty-sands, sands and gravel and the bedrock between 35 - 45 m depth

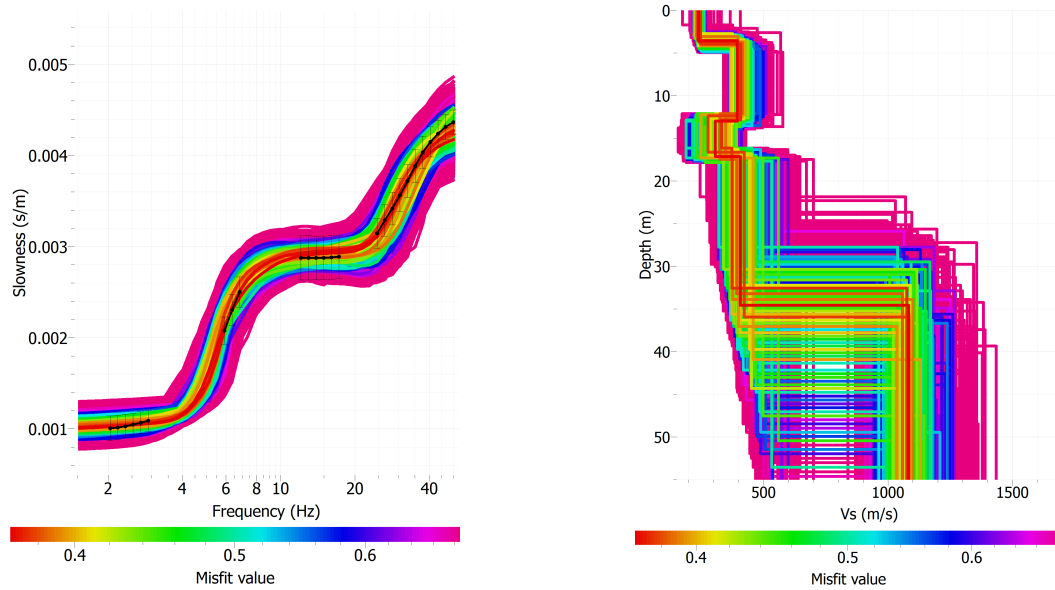


Figure 9. Left: Measured dispersion curve for the site (black dots) with calculated dispersion curves for each model (color scale depending on the misfit level). Right: Vs velocity models with satisfactory misfit values (< 0.6). Parameterization by five homogeneous layers including the velocity inversion around 12 m depth

4. DISCUSSIONS AND CONCLUSIONS

This work has been done in the frame of PORTE project supported by the European ERDF funds as well as the Provence Alpes Côte d'Azur region. This project aims to create an instrumental platform dedicated to the observation of different areas of interest in order to obtain a long-term recording of parameter characterizing the natural environment between and during crisis. On a human scale, the understanding / prediction of natural risks requires a recurrent observation of their actions in order to identify possible precursor signs that would make it possible to prevent a crisis, and to quantify threshold values of constraints that would improve the accuracy of the models. The project will benefit from the situation of the Provence - Alpes - Côte d'Azur region. Because of its location on the border between the Alps and the Mediterranean Sea, its geodynamic context, its extreme geography (from the deep basin to the high mountain in less than 80 km at the Côte d'Azur), its numerous stakes (human, material, economic), and the continuous population density increase, in particular on the coast, the PACA region is an ideal laboratory to study the natural hazards and associated risks (earthquake, landslide and rock fall, flood, tsunami, marine submersion, ...). PORTE is therefore part of a global multidisciplinary approach involving several research centres that will help on the analysis of the territorial resilience and the human behavior in disaster situations for a better integration into public policy and territorial planning. It will allow the development of a strong synergy in the field of the observation of telluric and climatic phenomena and the apprehension of associated risks.

The future vertical array will complete a set of seismological instrumentations that have already been put in the area, such as the French Accelerometric Network who equipped a high rise RC building in the vicinity of the borehole array in order to better understand the behavior of the building and its interaction with the seismic wavefield. We planned to set up 4 couples of velocimeter/accelerometer at 4 different depths (Surface, 10m, 30m and bedrock). The recordings will help to study the wave propagation through the soil column in order to better catch the seismic response of the soil and the sedimentary basin.

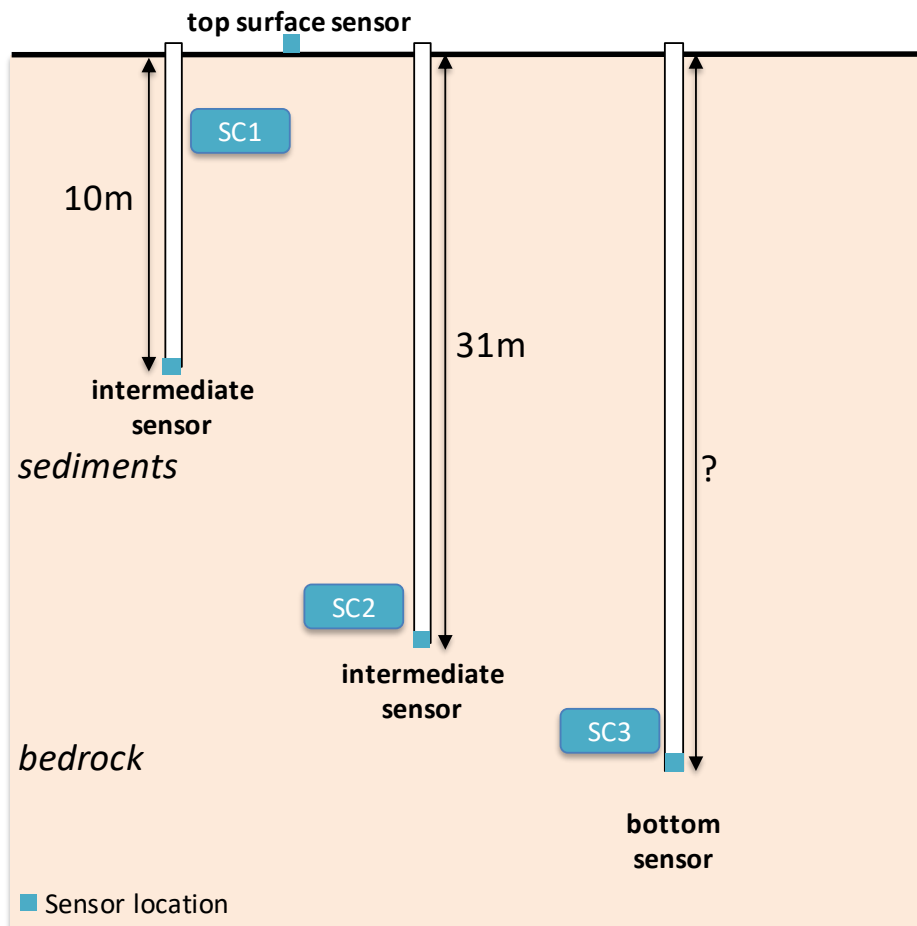


Figure 10. Scheme of the future installation

5. REFERENCES

- Bonilla L F, P. Gueguen, F Lopez-Caballero E. D Mercerat and C Gelis. Prediction of non-linear site response using downhole array data and numerical modeling: The Belleplaine (Guadeloupe) case study. *Physics and Chemistry of the Earth Parts A/B/C* DOI10.1016/j.pce.2017.02.017
- Fondasol (2016). Construction de l'Institut Méditerranéen du Risque, de l'Environnement et du Développement Durable (IMREDD), Nice, Mission G2 – Phase AVP, 53p., juin 2016
- Guéguen P., Langlais M., Douste-Bacqué I., and the members of the RAP scientific board (2015). Recent scientific results from the instrumented sites and structures led by the French Accelerometric Network : examples of the Grenoble and Belleplaine vertical arrays, *Proceedings of the 6th International Conference on Earthquake Geotechnical Engineering*, 1-4 November, Christchurch, New Zealand.
- Serratrice J. F (2016). Mesures des propriétés cycliques des sols limoneux ou argileux au laboratoire, *Actes des Journées Nationales de Géotechnique et de Géologie de l'Ingénieur*, 6-8 July, Nancy, France.
- Wathelet, M. (2008) An improved neighborhood algorithm: parameter conditions and dynamic scaling. *Geophysical Research Letters*, 35, L09301
- Wathelet, M., D. Jongmans, M. Ohrnberger, and S. Bonnefoy-Claudet (2008). Array performances for ambient vibrations on a shallow structure and consequences over V_s inversion. *Journal of Seismology*, 12, 1-19.
- Zeghal M., Elgamal A.W. (2000). A review of site seismic response using vertical arrays, *Proceedings of the 12th World Conference on Earthquake Engineering*, 30 January - 4 February, Auckland, New Zealand.

- Vamvatsikos D, Cornell CA (2002). Incremental dynamic analysis. *Earthquake Engineering & Structural Dynamics*, 31(3): 491-514.
- Tsinidis G, Rovithis E, Pitilakis K, Chazelas J-L (2014). Dynamic centrifuge testing of rectangular tunnels in soft soils, *Proceedings of the 2nd European Conference on Earthquake Engineering and Seismology*, 24-29 August, Istanbul, Turkey.
- Vu D.D (2002).Strength properties of Metakaolin-blended paste, mortar and concrete,*Ph.D. Thesis*, Faculty of Civil Engineering and Geosciences,Delft Technical University of Technology, The Netherlands.
- Clough RW, Penzien J (1993).Dynamics of Structures, 2nded., McGraw-Hill Book Company, New York.
- Argyroudis S, Kaynia AM (2014). Fragility functions of highway and railway infrastructure. In: Pitilakis K, Crowley H, Kaynia AM (eds) SYNER-G: Typology definition and fragility functions for physical elements at seismic risk. *Geotechnical, Geological and Earthquake Engineering* 27, Springer Netherlands, pp 299-326.