16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING THESSALONIKI
18 - 21 JUNE 2018

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

Nathalie DUFOUR[1], Jean-Baptiste PAYEUR[2], Etienne BERTRAND[2], Diego MERCERAT[2], Julie REGNIER[2], Vincent VANCRAENENBROECK[3], Morgan ALLIAUME[3], Frédéric CAPELLE[3], Philippe LANGLAUDE[2], Michel PERNOUD[2], Hélène CALISSANO[1], Laurent BATILLIOT[1], Marlène COUDERT[1]

ABSTRACT

Because of its geomorphology, 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 the lithological site effect. These effects can amplify the seismic motion in soft layers overlaying hard bedrock encountered for example in the Alpine valleys. The quantitative assessment of the ground motion 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 sedimentary basin for instance. To better understand these site effects it seems interesting to record the the seismic waves by setting up verticals seismological arrays.

Within the framework of the PORTE project, supported by the PACA (Provence Alpes Côte d'Azur) region and the European Regional Development Fund (ERDF), one of the objectives 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 geology of this site consists in saturated alluvium based on a Pliocene marl bedrock, whose depth is estimated around 40 m. The soil column is composed of heterogeneous sand and ruble layers with inclusions of silt and clay horizons. Geophysical measurements (MASW and AVA) allowed us to define a S-wave velocity profile while laboratory measurements on core drillings samples provided the mechanical behaviour of the different sedimentary layers.

In a few months, an instrumentation combining accelerometric and velocimetric sensors will be set up at four depths (surface, -10 m, -31 m and bedrock) and will continuously record the seismicity of the area. This instrumentation will be complemented by pore water pressure dynamic measurements.

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

3Cerema, 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 (e.g. Dobry et al., 1971). This data was used 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 (Shima, 1962). 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 (Japan) (Katayama et al., 1990), Lotung (Taïwan) (Tang, 1987), Hualien (Taïwan) (Tang et al., 1991), Port Island (Japan) (Iwasaki et Tai, 1996), and Treasure Island (USA) (deAlba et al., 1994) sites. Since the 1980's, data from downhole seismic arrays that include pore-pressure piezometers became increasingly available (Wildlife Refuge, USA (Holzer al al., 1989) and Lotung (Zeghal et Elgamal, 1993) sites for example). In the 90's Japan deployed a network composed of nowadays 688 sites with a surface and a downhole sensor (KiK-net). 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 three sites have been equipped with surface and downhole 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) Belle-Plaine 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 pore-pressure sensors complete the set-up (Bonilla et al, 2017)
(3) Cadarache borehole in South-East France: 115 m depth, the Cadarache vertical array is equipped with velocimeters.

Within the framework of the PORTE project, supported by the PACA (Provence Alpes Côte d'Azur) region and the European Regional Development Fund (http://ec.europa.eu/regional_policy/en/funding) a fourth vertical seismological network will be installed in Nice, in the lower Var valley. Il 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. For information purposes, this system is 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, the highest seismic hazard zone in metropolitan France (see Figures 2 and 3). The future station consists in a vertical arrays of three sensors as shown in figure 2. For the moment, two boreholes have been drilled, in order to locally investigate the geotechnical conditions and to enable the installation of downhole sensors.

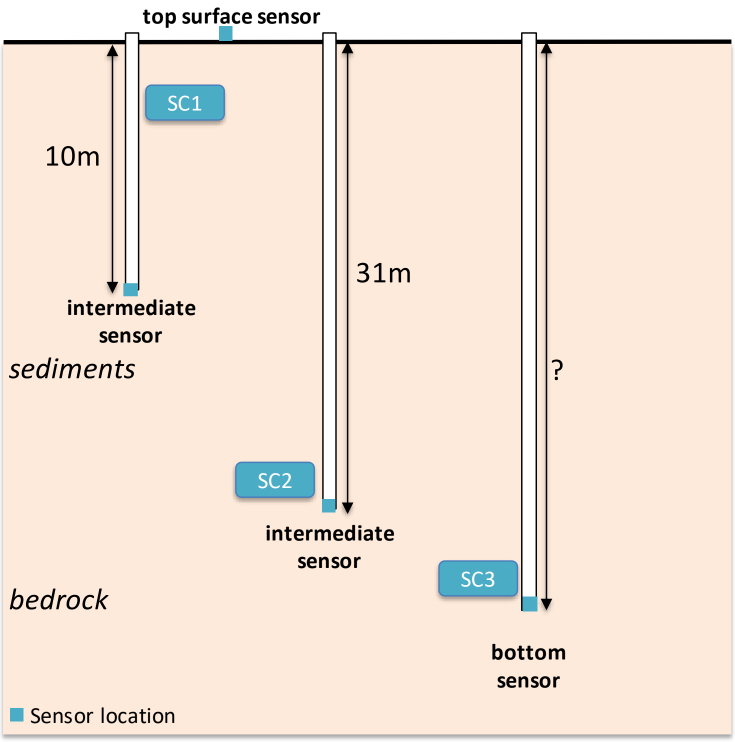

Figure 1. Scheme of the future installation

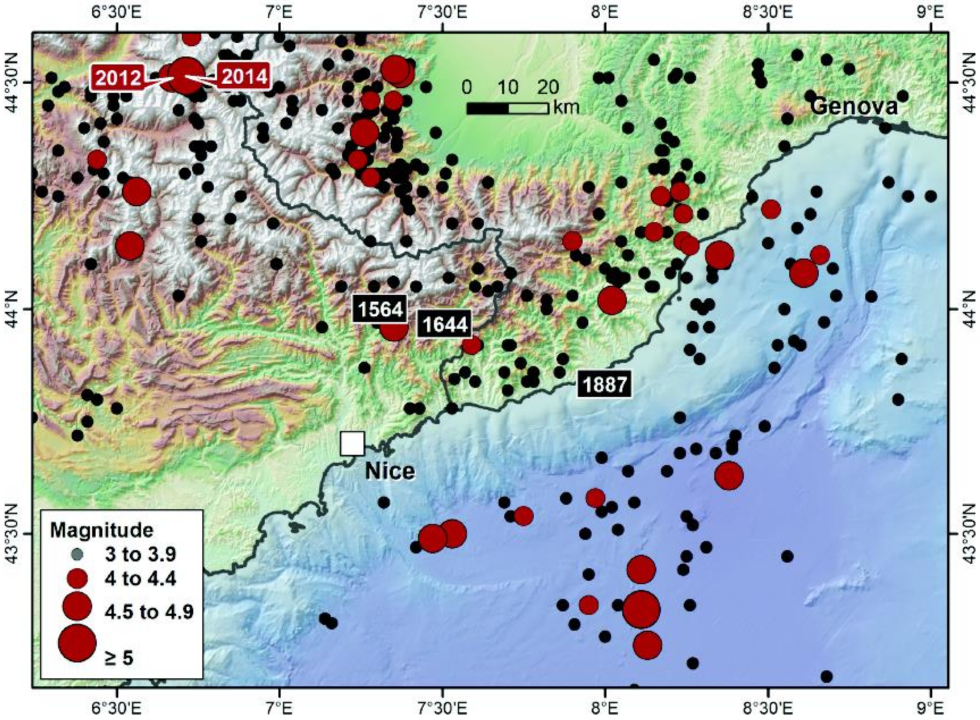

Figure 2. Regional instrumental seismicity from BCSF catalog (1960-2015). Nice city shown by a white square. Two main Barcelonnette events of 2012 and 2014 are shown in the upper-left area and three reference historical events located by black rectangles. After (Fernandez Lorenzo et al., 2017)

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 meters of coarse alluvium with great sandy and gravely lenses. Geotechnical surveys have been carried out to characterize the zone (e.g. Dubar, 2003). Generally, 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 $V_{s,30} = 235$ 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.

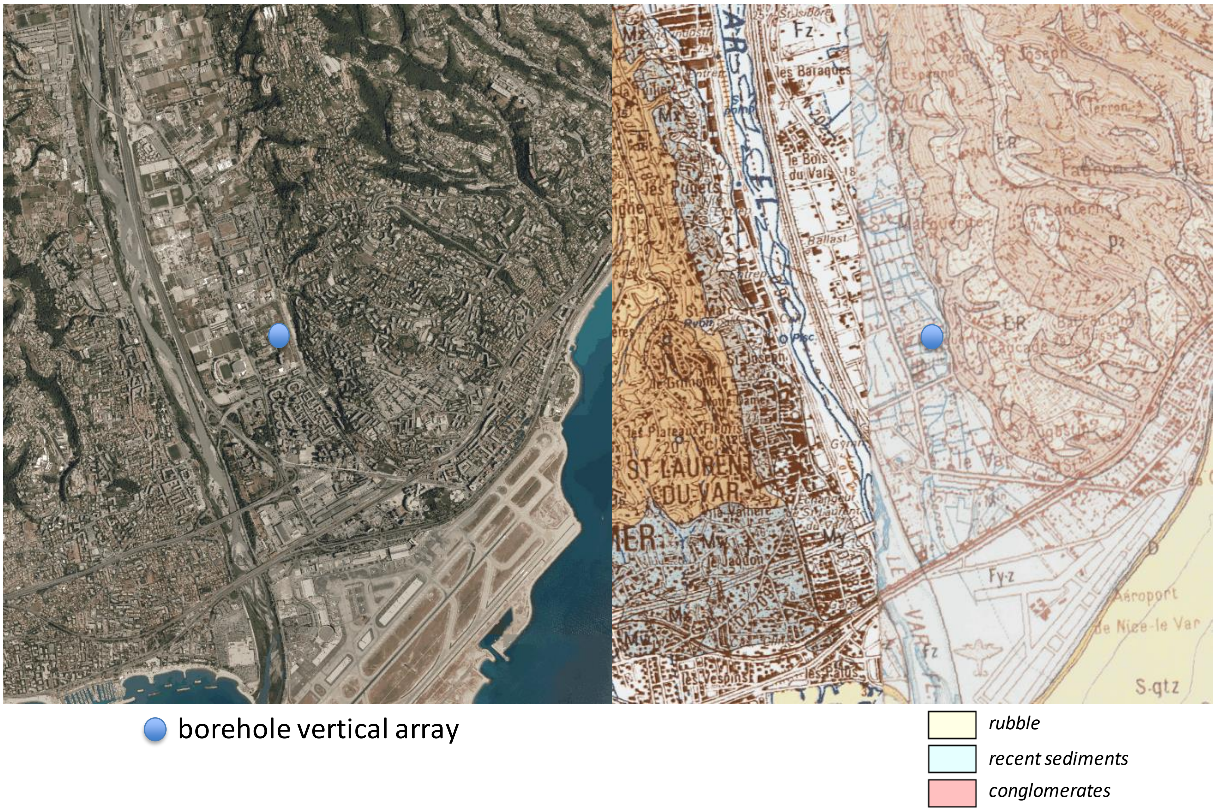

Figure 3. The future Nice borehole test site : satellite image on the left side and geological map on the right side

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 the 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 1. Measured values of unit weight and water content are also given in Table 2.

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 4, 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	$13.9 \le \gamma \le 25.8$	$6.0 \le w \le 12.7$
Silt -Organic clay	12.5- 17.5	5.0	$17.4 \le \gamma \le 20.1$	10.5
Sand and rubble	17.5- 28.5	11.0	22.5	-

Figure 4. 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 tests (SP1, SP2 and SP3 locations shown in Figure 8) have been done in three open boreholes, 20 m depth each, following the NF EN ISO 22476-4 norm. Twenty-four PMT have been performed in the upper layers of soil and can be related to the first sand and rubble layer; height PMT can be related to the silt - organic clay profile and five to the upper part of the second sand and rubble layer.
The mean pressiometric values Em (pressiometric modulus) and pl* (net limit pressure) related to the site soil layers are given in Table 3.

Table 3 :Pressiometric values for each soil profile

Soil	**Em_min (MPa)**	**Em_mean (MPa)**	**Em_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.

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 indicate 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.

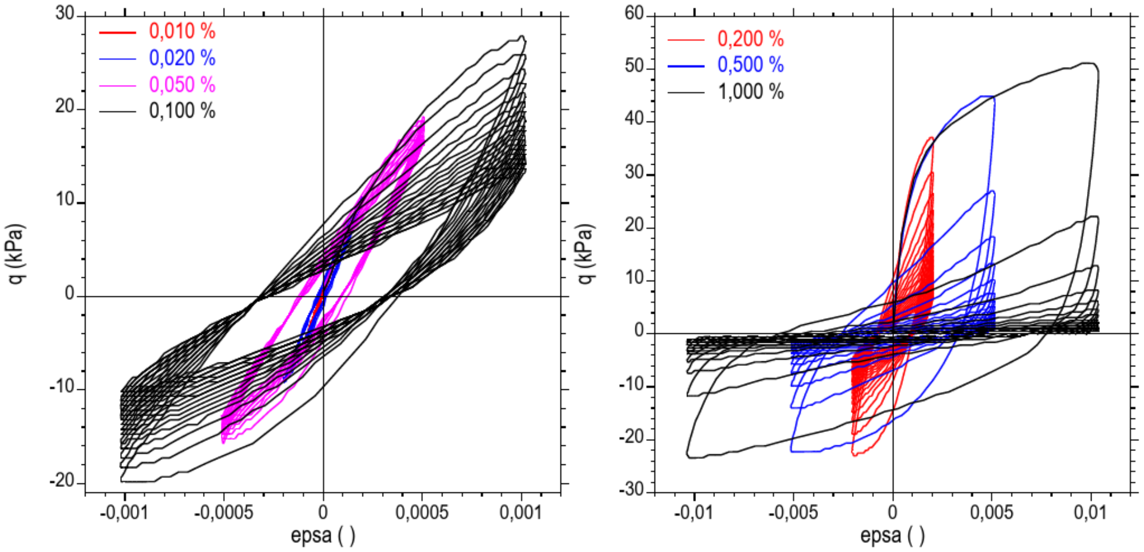

Figure 5. Relationships between deviatoric stress q and axial strain epsa – Several successive sequences of undrained cycles in a range of axial strain : 0.010 % - 0.020 % - 0.050 % - 0.100 % - 0.200 % - 0.50 % - 1.000 % on a sample located at 0.80 m depth

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 is silty sand (20,0 m depth). The test consists in applying several successive sequences of undrained cycles in a range of axial strain 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 strain, obtained from a triaxial testing on a sandy sample located at 0,8 m depth, is presented in Figure 5.

Following Serratrice's method (Serratrice, 2016), a Fourier's serial approximation of the experimental records allows the precise identification of secant Young modulus and hysteretic damping ratio D for each axial strain (0.010 % - 0.020 % - 0.050 % - 0.100 % - 0.200 % - 0.50 % - 1.000 %). Relationships between secant Young modulus and axial strain (epsaDA) and between hysteretic damping ratio and axial strain are plotted in Figure 6.

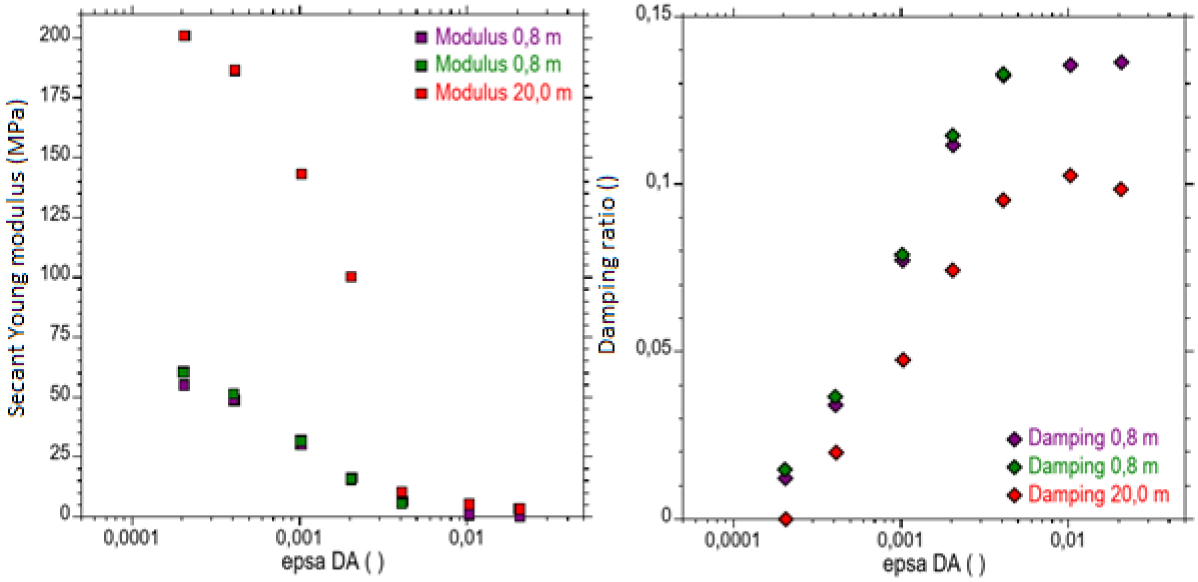

Figure 6. Degradation curves - Left : Relationships between secant modulus and axial strain – Right : Relationships between hysteretic damping ratio and axial strain

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 in ambient noise arrays of eleven 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 twenty-four 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.

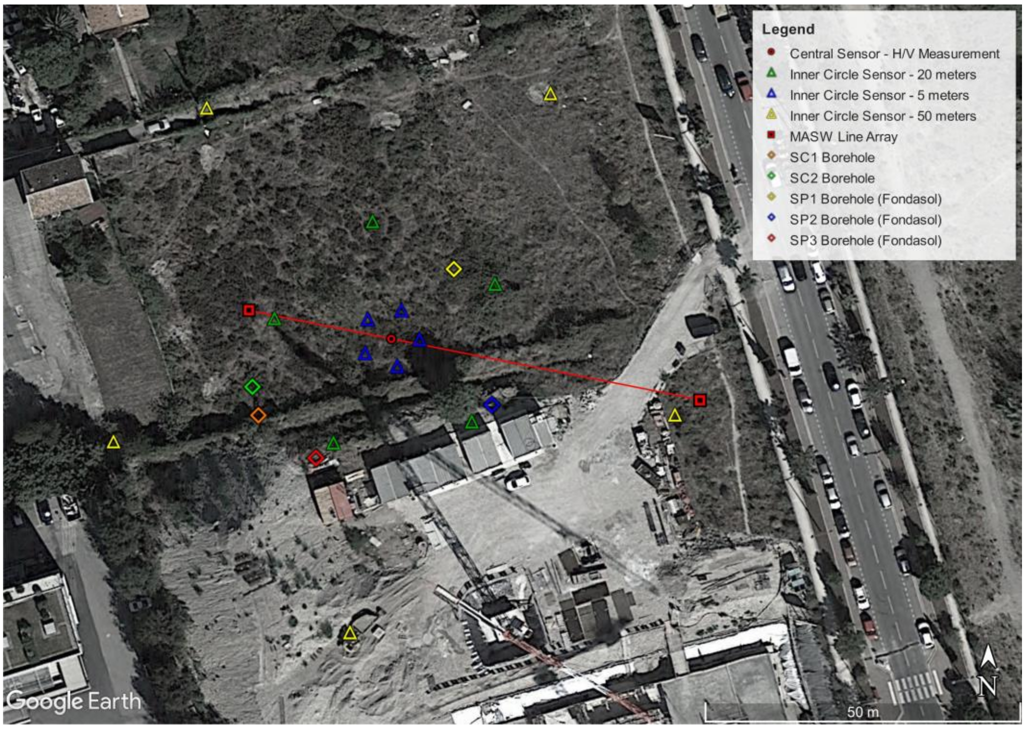

Figure 7. Position of the stations of the seismic array (triangles) and the MASW profile. Boreholes SC1 and SC2, where accelerometers will be installed, are shown by orange and green diamonds. Geotechnical boreholes SP1, SP2 and SP3 by yellow, blue and red diamonds

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 Vs around 250 m/s, followed by a thick layer of gravel and sandy material (Vs ~ 380 m/s) down to 30 - 35 m depth where the bedrock (Vs ~ 1200m/s) is found.

One step further, taking into account the geotechnical in-situ tests measurements (from SP1, SP2 and SP3 boreholes) and laboratory characterization of soil samples (from SC1, SC2 boreholes) (see Tables 1, 2 and 3, Figures 5 and 6), 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 Vs around 250 m/s down to 3 - 4 m depth, followed by a thick layer of gravel and sandy material (Vs ~ 420 m/s), intercalated by a 5 m thick low velocity layer with a Vs ~ 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).

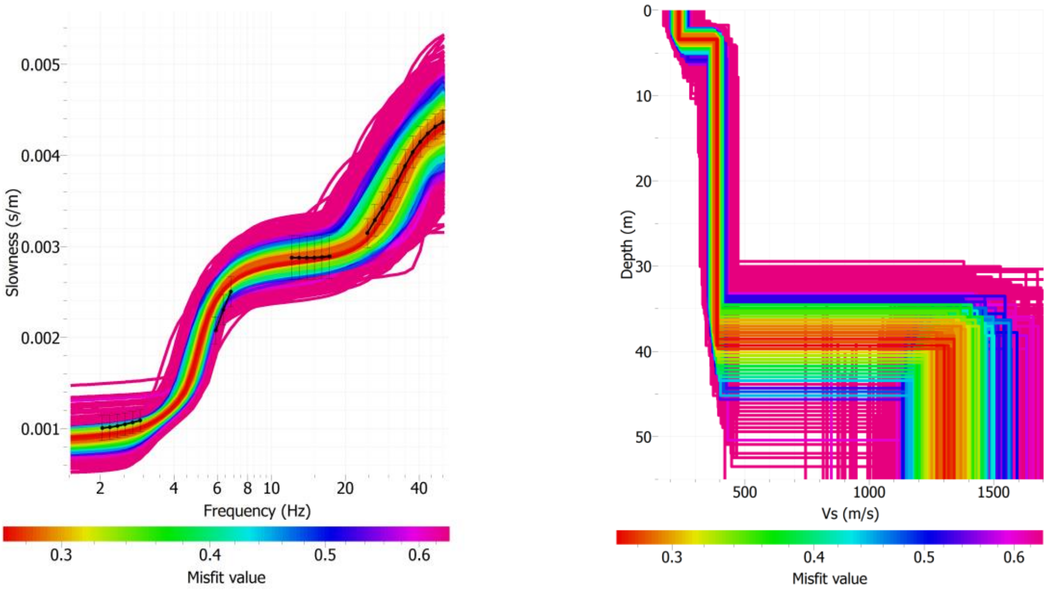

Figure 8. Left: Measured dispersion curve for the site (black dots) with calculated dispersion curves for each model (color scale depending on the misfit level). Right: Vs velocity models with satisfactory misfit values (< 0.6). Parameterization by three homogeneous layers corresponding to silty-sands,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

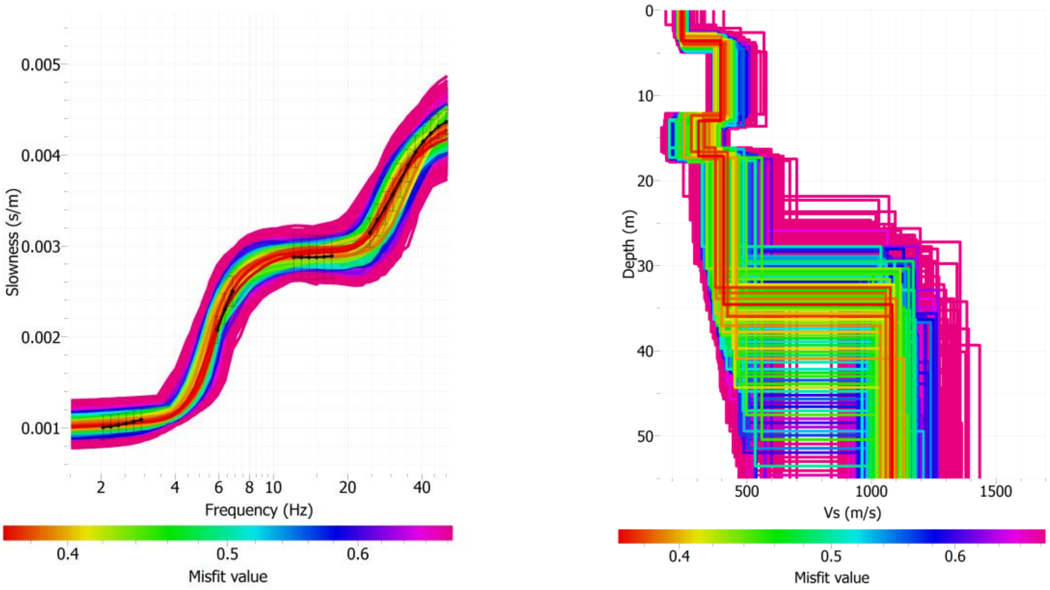

Figure 9. Left: Measured dispersion curve for the site (black dots) with calculated dispersion curves for each model (color scale depending on the misfit level). Right: Vs velocity models with satisfactory misfit values (< 0.6). Parameterization by five homogeneous layers including the velocity inversion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

4. CONCLUSIONS

This work has been done in the framework of PORTE project supported by the European Regional Development Fund 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. The understanding of natural risks requires a recurrent observation of their actions in order to identify possible precursor phenomenon 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 location 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 behaviour 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 installed 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 behaviour of the building and its interaction with the seismic wavefield. In order to be able to record a wide range of seismic motion, we planned to set up four couples of velocimeter/accelerometer at four different depths (Surface, 10m, 30m and bedrock). The recordings will help to study the wave propagation through the soil column in order to better assess the seismic response of the soil and the sedimentary basin.

5. REFERENCES

Bonilla L F, Gueguen P., Lopez-Caballero F, Mercerat E. D. and Gelis C. (2017). 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 D*OI10.1016/j.pce.2017.02.017

de Alba, P., Benoît, J., Pass, D.G., Carter, J.J., Youd, T.L. and Shakal, A.F. (1994). Deep Instrumentation Array at the Treasure Island Naval Station, in The Loma Prieta, California, Earthquake of October 17, 1989: Strong Ground Motion and Ground Failure, *U. S. Geol. Surv. Prof. Pap.* 1551-A, R. D. Borcherdt, Ed., U.S. Geological Survey, Washington D.C., A155-A168.

Dobry, R., Whitman, R. V. and Roesset, J. M. (1971). Soil Properties and the One-Dimensional Theory of Earthquake Amplification, *Research Report, R71-18*, School of Engineering, Massachusetts Institute of Technology.

Dubar, M. (2003). The Holocene deltas of Eastern Provence and the French Riviera: geomorphological inheritance, genesis and vulnerability. Géomorphologie : relief, processus, environnement 9, 263– 270. doi:10.3406/morfo.2003.1189.

European Committee for Standardisation, 2004. EN 1998-1: Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings.

Fernandez Lorenzo G. W., Santisi d'Avila M. P., Deschamps A., Bertrand E., Mercerat E. D., Foundotos L. and Courboulex F. (2017). Numerical and empirical seismic response simulation of buildings: the case study of Nice prefecture. *Earthquake Spectra*, 2017, DOI 10.1193/042216EQS064M.

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 6thInternational Conference on Earthquake Geotechnical Engineering*, 1-4November, Christchurch, New Zealand.

Holzer, T.L., Youd, T.L. and Hanks, T.C. (1989). Dynamics of Liquefaction During the 1987 Superstition Hills, California, Earthquake, *Science*, Vol. 244, pp. 56-59.

Iwasaki, Y. and Tai, M. (1996). Geotechnical Aspects of the January 17, 1995 Hyogoken-Nambu Earthquake: Strong Motion Records at Kobe Port Island, *Soils and Foundations*, Special Issue, Jan., pp. 29-40.

Katayama, T., Yamazaki, F., Nagata, S., Lu L. and Turker, T. (1990). A Strong Motion Data Base For the Chiba Seismometer Array and Its Engineering Analysis, *Earthquake Engineering and Structural Dynamics*, Vol. 19, 1089-1106.

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.

Shima, E. (1962). "Modification of Seismic Waves in Superficial Layers as Verified by Comparative Observations on and Beneath the Surface," *Bulletin of Earthquake Research Institute*, Tokyo, Vol. 40, 187-259.

Tang, H.T. (1987). Large-Scale Soil Structure Interaction, *Report No. NP-5513-SR*, Electric Power Research Institute, Palo Alto, California.

Tang, H.T., Kokusho, T., Nishi, K., Kataoka, T. and Cheng, Y.H. (1991). The Hualien Large-Scale Seismic Test for Soil-Structure Interaction Research, *SMIRT 11 Transactions*, K04/4, pp.69-74.

Wathelet, M. (2008) An improved neighborhood algorithm: parameter conditions and dynamic scaling. *Geophysical Research Letters*, 35, L09301

Wathelet, M., Jongmans D., Ohrnberger M., and Bonnefoy-Claudet S. (2008). Array performances for ambient vibrations on a shallow structure and consequences over V_s inversion. *Journal of Seismology*, 12, 1-19.

Zeghal, M. and Elgamal, A.W. (1993). Lotung Site: Downhole Seismic Data Analysis, Report Submitted to EPRI, Department of Civil Engineering Rensselaer Polytechnic Institute, Troy, New York.

Zeghal M., Elgamal A.W. (2000). A review of site seismic response using vertical arrays, *Proceedings of the 12thWorld Conference on Earthquake Engineering*, 30 January - 4February, Auckland, New Zealand.