CONTRIBUTION OF PETRO-GEOPHYSICS FOR SEISMIC SITE RESPONSE ANALYSIS

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Abstract

In low to moderate seismicity zones, specific site response has to be numerically forecasted with 1D, 2D or 3D models, based on the available data from local geology and the dynamic parameters of the different layers below the surface (mainly Density, Vp, Vs and Damping).

In France, the geotechnical investigations on a given site were historically conducted down to 100 to 200m, which is the depth of influence of the Soil Structure Interaction of the main buildings and considered as the "engineering bedrock".

However, due to impedance contrasts, seismic amplifications can be generated between the "seismological bedrock", defined by Kawase [1] as the very old geological layers for which Vs > 3000 m/s, and the "engineering bedrock". The "seismological bedrock" can be located several kilometers below the surface and has been reached by very deep boreholes drilled by the exploration department of oil and gas companies in France between 1950 and 1970.

Very high-resolution (15cm) geophysical measurements (sonic, gamma-ray, neutron) were conducted on the whole length of the holes, giving abundant data concerning the variability on geology, Vp and porosity values, among others parameters.

Furthermore, many ultra-sonic measurements on deep core samples have given some empirical relations between Vp/Vs ratio and geology, mineralogy, Vp, depth, porosity and saturation, as reported by Mavko et al. [2] among many others.

This study gives few numerical analysis of some deep boreholes measurements in order to quantify:

i) the amplification of the seismic signal due to the layers located between the "seismological bedrock" and the "engineering bedrock", in the range 0.1-50 Hz,

ii) the influence of the velocity profile discretization and Vp/Vs relations,

iii) the quantification of the intra-layer variability (trend, harmonic mean, variance and correlation length) at a local and regional scale and its influence on the transmitted waves.

Some examples of 1D soil column transfer function are calculated in the frequency domain with the open source Finite Element software *Code_Aster*, with dedicated operators for wave propagation and Karhunen-Loeve random field generation.

The velocity profile of the soil between the engineering bedrock and the seismological bedrock is not always constant or gently increasing but shows velocities contrasts that can produce moderate amplifications at some resonance frequencies in the frequency range of seismic interest (0.1-35 Hz).

Keywords: site response; geophysics; Vs profile; soil variability

1. Introduction

In low to moderate seismicity zones, specific site response has to be numerically forecasted with 1D, 2D or 3D models, based on the available data from local geology and the dynamic parameters of the different layers below the surface (mainly Density, Vp, Vs and Damping).

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However, due to impedance contrasts, seismic amplifications can be generated between the "seismological bedrock", defined by Kawase [1] as the very old geological layers for which Vs > 3000 m/s, and the "engineering bedrock". The "seismological bedrock" can be located several kilometers below the surface and has been reached by very deep boreholes drilled by the exploration department of oil and gas companies in France between 1950 and 1970.

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iv) the amplification of the seismic signal due to the layers located between the "seismological bedrock" and the "engineering bedrock", in the range 0.1-50 Hz,

v) the influence of the velocity profile discretization and Vp/Vs relations,

vi) the quantification of the intra-layer variability (trend, harmonic mean, variance and correlation length) at a local and regional scale and its influence on the transmitted waves.

2. Petro-Geophysics measurements and correlations for dynamic characteristics

When looking for oil and gas, the Exploration Department of oil companies need to drill very deep holes in places where potential reservoirs had been pointed out by 2D seismic reflexion analysis.

In order to get the maximum of information about the potentiality of the geological formations to be a reservoir for oil or gas, they perform numerous measurements into the boreholes such as Resistivity log, Gamma Ray log, Neutron log, Sonic log, ... The stratigraphic and palynologic analysis of the cuttings provide informations about the geological age of the formations.

The Sonic log consists in measuring the slowness of compressional waves in the rock surrounding the hole, filled with mud, with a long probe composed of a wave generator (about few kHz) and 2 receivers. The slowness of the compressional waves Sp, expressed in µs/feet, is measured every half feet (15.24 cm). The velocity of the compressional waves Vp in m/s, can be deduced with Eq. (1):

$$Vp = 0.3048 * 1.10^6 / Sp \qquad (1)$$

In most cases, the subsurface upper formations of Quaternary or early Tertiary ages are unconsolidated and need to be cased, which makes the sonic log impossible in the first tens or hundreds of meter depth. The average value of Vp in these formations can sometimes be estimated when a Vertical Seismic Profiling (VTS) is performed in the hole with explosive sources at the surface and Downhole-like measurement at some specific depths, mainly at the geological formations interfaces.

Shear Velocity log has been developed more recently (around 1980) and before that petrophysics engineers have been interested into estimating the Vp/Vs ratio, mostly based on laboratory ultrasonic measurements in rock cores, and its dependences with lithology, porosity and pressure.

For consolidated rocks, Vp/Vs ratio is typically between 1.5 and 3, which leads to Poisson coefficient ν between 0.1 and 0.4375, respectively, according to Eq. (2).

$$V_p/V_s = \sqrt{\frac{2\cdot(1-\upsilon)}{1-2\cdot\upsilon}} \qquad (2)$$

Many relations between Vp and Vs for saturated soils or rocks have been proposed in the literature [2] and we selected 2 of them for this study:

(i) the relation proposed by Castagna et al. [3], also known as “mudrock line”, and given in Eq. (3) for velocities in m/s. This relation is valid for Vp between 1360 and 4500 m/s [4] and for materials whose matrix is mainly composed of clay and sand (mudrock, sandstone, claystone,…). It is also coherent for low Vs values that leads to the Vp value for water (around 1500 m/s). For limestones and dolostones, [3] gives Vp/Vs ratio around 1.9 and 1.8, respectively.

$$Vp = 1.16\,Vs + 1360 \quad \Leftrightarrow \quad Vs = 0.862\,Vp - 1172 \qquad (3)$$

(ii) the relation proposed by Brocher [4] for estimating Poisson ratio ν from Vp in km/s with Eq.(4).

$$\nu = 0.8835 - 0.315Vp + 0.0491Vp^2 - 0.0024Vp^3 \qquad (4)$$

As for Vp versus Vs relations, many correlations have been developed to link bulk density and Vp. In this study, the relation from Gardner [5] was applied, as given by Eq.(5) for Vp in m/s and ρ in kg/m3.

$$\rho = 309\,Vp^{0.25} \qquad (5)$$

Finally, frequency independent damping D = 1/(2Q) is calculated, assuming a Vs dependency, with the relation given on [4], Eq.(6), with Vs in km/s. A sensitivity study will also be performed based on Eq.(7).

$$Q = -16 + 104.13Vs - 25.225Vs^2 + 8.2184Vs^3 \qquad (6)$$

$$Q = Vs/10 \qquad (7)$$

Shear modulus and Young’s modulus can also be calculated with Eq.(8).

$$E_{max} = 2\,(1+\nu)\,G_{max} = 2\,(1+\nu)\,\rho\,Vs^2 \qquad (8)$$

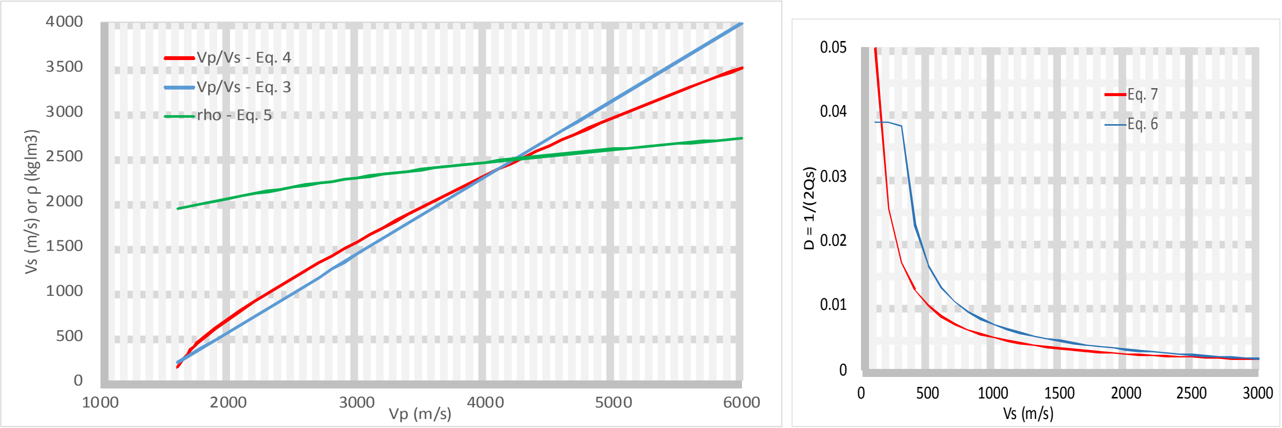

Fig. 1: (left) Vp/Vs relations and ρ/Vp relation, (right) AH/Vs relations

3. Deep Borehole Sonic logs

For this study, we selected 5 boreholes located in South West part of France for which sonic log were available, starting in the Upper Cretaceaous (Ks) and ending in the Paleozoïc (P-Socle) considered as the seismic substratum, and named LVD, SFX, BLC, SMB and ART .

Slowness values have been picked up from scanned images of original paper sonic logs. The different formations are identified based on the final geological log of the report. The main characteristics of the 5 boreholes are given in Table 1 and the Vp velocity logs are given on Figure 2, with different colors standing for geological layering.

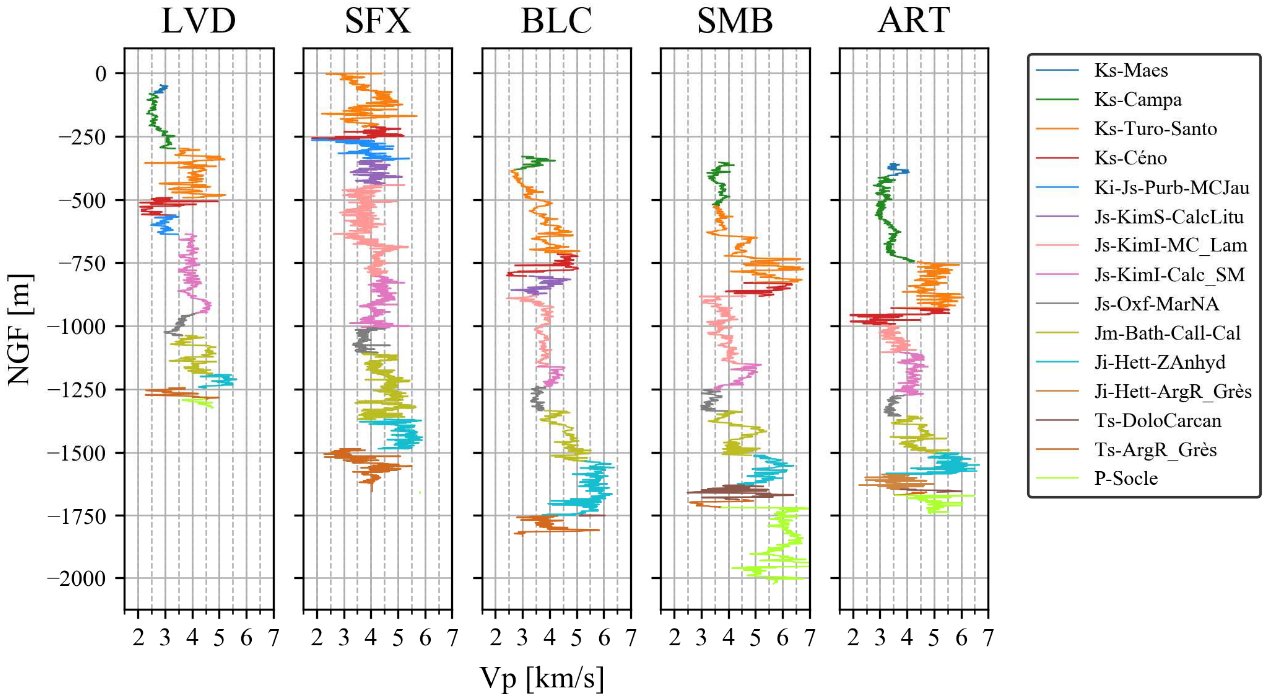

Fig. 2 : raw Vp values measured with Sonic tool at the 5 boreholes, colored by geological formation, see legend on the left part, Ks/Ki :upper/lower Cretaceous, Js/Jm,Ji : upper, medium, lower Jurassic, Ts ; upper Trias, P : Paleozoic ; 0 NGF is Sea Level

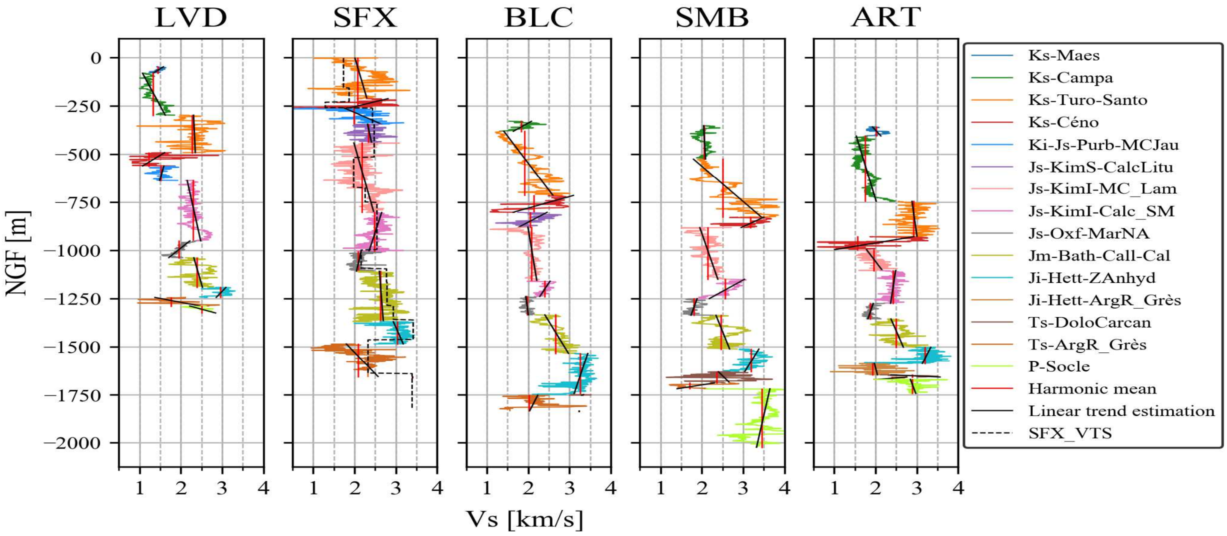

Fig. 3 : _grad (black) and _harmo (red) Vs profiles calculated on _raw Vs values (same colors as Fig. 2) with Eq. (4). Harmonic mean (_harm: red) and linear trend (_grad: black) per geological formation are also shown

4. Vs variability by geological formation

Vertical variability of soil properties is modeled by using the random field theory, detailed in [6], defined by two functions (1) a probability density function which is considered in this study as log-normal (positive-skewed) and (2) an autocorrelation function, which expresses the correlation coefficient between two points separated by a distance h, called lag distance. The spatial correlation model used in this study is the 1D Markov model that has an exponentially decaying correlation function, cf. Eq. 9, where Lc is the scale of fluctuation, which may be interpreted as the separation distance over which soil property are largely uncorrelated, and β^2_{RF} is the variance at h= 0.

$$\rho(h) = \beta_{RF}^2 \exp\left(\frac{-2.h}{L_c}\right) \qquad (9)$$

The computation of variogram function is a more appropriate and easiest way to describe spatial relations, and obtain Lc and β. The variogram function is defined as the variance between data at a particular lag distance h:

$$2.\gamma(X_i, X_{i+h}) = 2.\gamma(h) = E\{[X_i - X_{i+h}]\} \qquad (10)$$

With the function $\gamma(X_i, X_{i+h})$ called the semi-variogram function (due to factor 2) is calculated wit Eq. 11, where N(h) is the number of data pairs separated by a length h.

$$\gamma(h) = \frac{1}{2.N(h)} \sum_{i=1}^{N(h)} [X_i - X_{i+h}]^2 \qquad (11)$$

The relationship between the variogram function and the autocorrelation function is:

$$\gamma(h) = \left(\beta_{RF}^2 - \rho(h)\right) \qquad (12)$$

Empirical variograms are estimated for LVD and SFX boreholes, cf. Fig.4, based on the detrended data (to obtain a stationary process). For each geological formation, a linear trend is computed and removed with Eq.(13), where z0 denotes the depth at the middle of the geological formation (see also Tab. 1).

$$Vs(z)\_detrend = Vs(z)\_measured \;/\; (a.(z-z0)+b) \qquad (13)$$

Tab. 1 : Vs harmonic mean and trend for the 5 boreholes

	SFX			LVD			ART			SMB			BLC		
Nature	**th**	**harmo**	**a**	**th**	**harmo**	**a**	**th**	**harmo**	**a**	**th**	**harmo**	**a**	**th**	**harmo**	**a**
Ks-Maes	-	-	-	33	1445	-7.6	47	2018	4.3	-	-	-	-	-	-
Ks-Campa	-	-	-	217	1318	2.5	340	1756	1.4	173	2059	0.3	52	1829	-8.4
Ks-Turo-Santo	210	2067	1.4	194	2264	0.2	183	2920	0.7	303	2509	5.4	334	1918	3.6
Ks-Céno	49	2074	-19.5	69	1228	-7.7	67	1564	-28.4	53	3175	-10.3	87	2131	-16.6
Ki-Js-Purb-MCJau	83	1985	10.8	77	1521	-1.3	-	-	-	-	-	-	-	-	-
Js-KimS-CalcLitu	97	2338	1.0	-	-	-	-	-	-	-	-	-	77	2054	-8.9
Js-KimI-MC_Lam	363	2186	1.3	-	-	-	108	1957	3.5	268	2147	1.6	280	2080	0.8
Js-KimI-Calc_SM	204	2483	-1.5	313	2301	1.0	170	2418	-0.7	100	2569	-8.5	79	2396	-3.1
Js-Oxf-MarNA	100	2093	-1.1	87	1946	-5.9	80	1877	-1.6	86	1801	-1.7	95	1970	0.6
Jm-Bath-Call-Cal	261	2619	0.4	154	2380	1.4	147	2492	2.0	175	2461	1.9	200	2665	2.9
Ji-Hett-ZAnhyd	116	3034	2.1	52	2953	-4.5	86	3201	-2.4	119	3190	-2.9	215	3251	-1.6
Ji-Hett-ArgR_Grès	-	-	-	-	-	0.0	59	1931	1.2	-	-	-	-	-	-
Ts-DoloCarcan	-	-	-	-	-	0.0	11	2890	105.4	58	2361	4.8	3	3308	-14.8
Ts-ArgR_Grès	171	2093	4.5	44	1762	24.7	12	2395	-56.2	30	1711	-29.8	80	2019	-2.4

NOTE : a =trend according to Eq. (13) in m/s/m, harmo=Vs harmonic mean in m/s, th = thickness in m

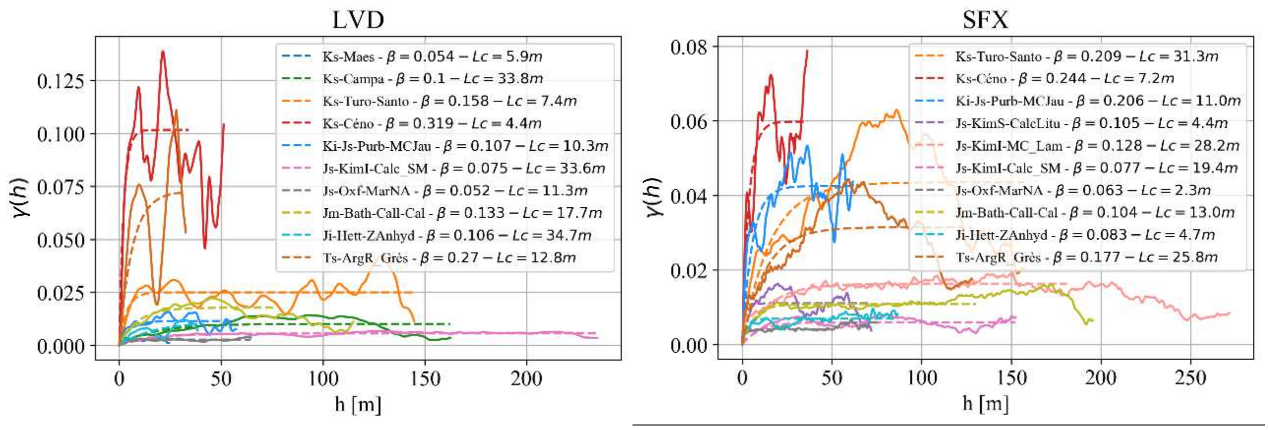

Fig. 4: Results of variograms (β and Lc) analysis for Vs sonic logs for LVD (left) and SFX (right)

NOTE : high β values indicates lithological variations (e.g limestone/marls) in a same geological unit or an inappropriate geological layering or a very low thickness of the layer (few values)

5. 1D soil column calculations

In order to characterize the frequency content transmitted by the Mesozoïc layers, linear 1D soil colums response are performed with the FEM software Code_Aster [7] in frequency domain. The results are displayed in terms of horizontal transfer function modulus, calculated between the Free-Field (Top of Cretaceous formation) and the seismic Substratum (Paleozoic formation).

The dynamic properties of the seismological substratum are considered constant for all the simulation with Vp = 5800m/s, Vs=3393m/s, ρ = 2705kg/m3 and damping D = 0.14%.

Soil columns are generated for the 5 boreholes with a mesh size around 3m due a software limitation of the total number of layers (<1000). This mesh size is sufficient for the propagation of waves up to 40Hz for Vs > 1000m/s. The velocity profiles are generated based on initial Vp profiles (0.3048m discretization) converted to Vs profiles using Eq.(3) or Eq.(4), and discretized by 3 different ways identified by the following names :

- _raw : the raw values are averaged (harmonic) 10 by 10 to get a value every 3.048m,
- _harm : the values are averaged (harmonic) by geological formation and this mean value is applied to each 3m sublayer of the geological formation, (see Fig. 3, red lines),
- _grad : for each geological formation, the trend on Vs is estimated by linear regression, cf Eq. (13), and this tendency is applied to each 3.048m sublayer of the formation, (see Fig.3, black lines).

5.1 Influence of Vp / Vs equation and damping equation

A sensitivity analysis has been made with both Eq.(3) and Eq.(4) for all the boreholes. The horizontal transfer functions shows similar shapes but Eq.(3) tends to slightly increase the amplitude and the stiffness of the soil column, cf. Fig. 5 for LVD_raw example. Eq.(4) will be preferred in the following examples as the Cretaceous, Jurassic and Triassic formations are made of many limestone formations.

No differences are observed concerning Eq.(6) and Eq.(7) for damping D, as the differences between both equations is small for Vs > 1000 m/s. Eq.(6) will be preferred in the following examples.

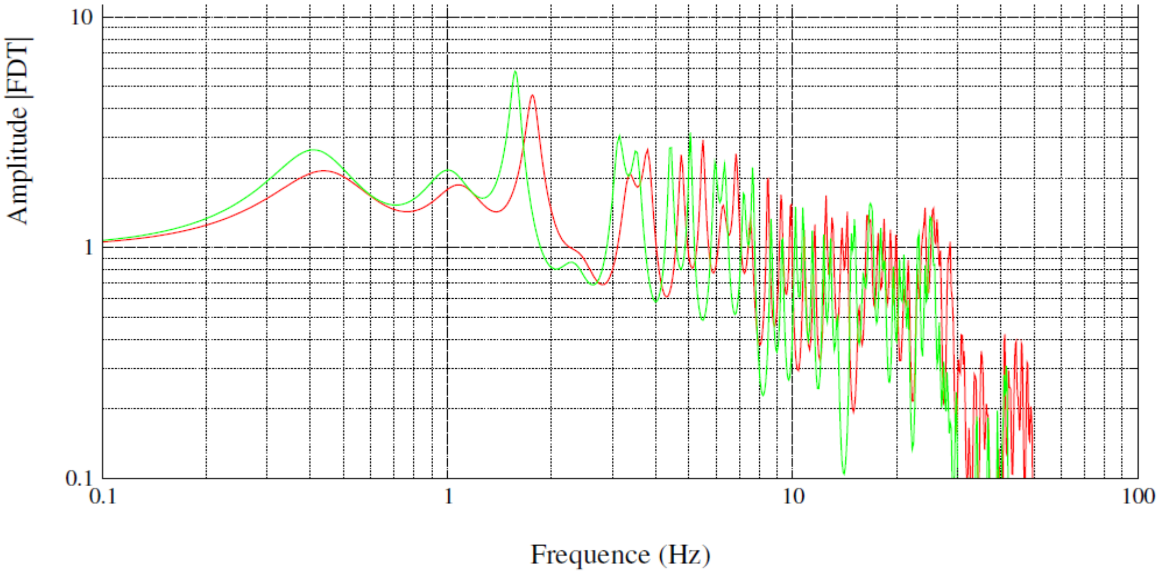

Fig. 5: Horizontal transfer function for LVD_raw for different Vp/Vs equations: Eq.(4) (red) and Eq.(3) (green)

5.2 Influence of Vs profile averaging

A Vertical Seismic Profile (VTS) was available for SFX borehole, consisting in 15 downhole shotpoints in surface and measures between 325 m and 2004 m depth, plotted with dotted line on Fig.2.

At this borehole a sensitivity study was performed with the 3 profiles defined in §5 (_raw, _harmo, _grad) and the _VTS profile, cf. Fig. 6. The first peaks at low frequency are almost at the same frequencies and amplitudes, the _harmo profile is the closest of the _raw profile. The _grad profile tends to be a little stiffer. The raw profile exhibit more fluctuations at high frequencies (> 5Hz).

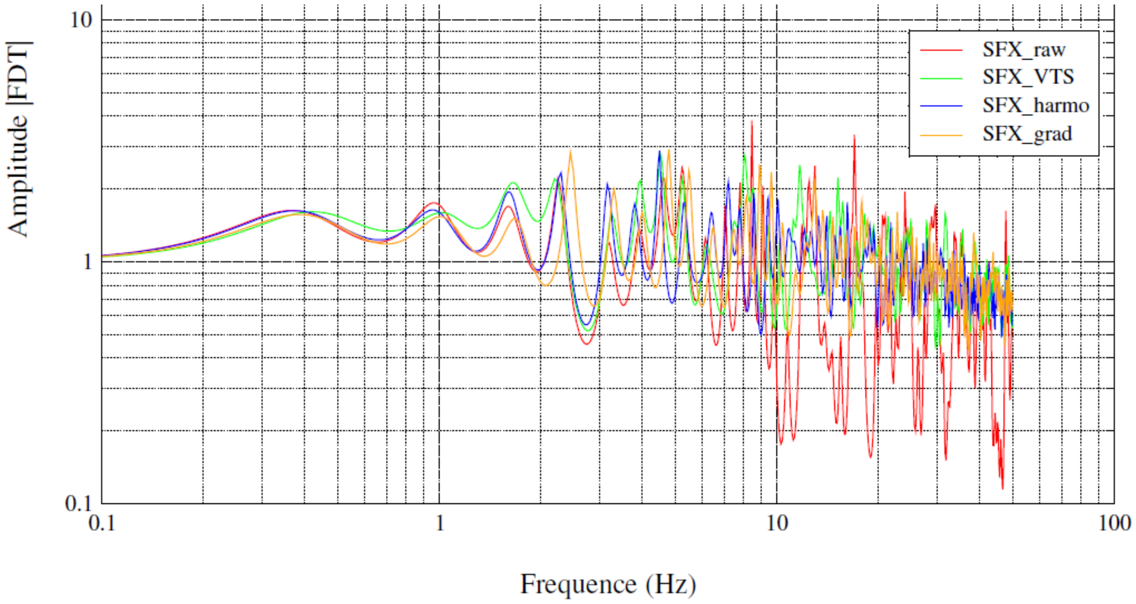

Fig. 6: Horizontal transfer function for SFX with 4 Vs profiles, averaging sensitivity

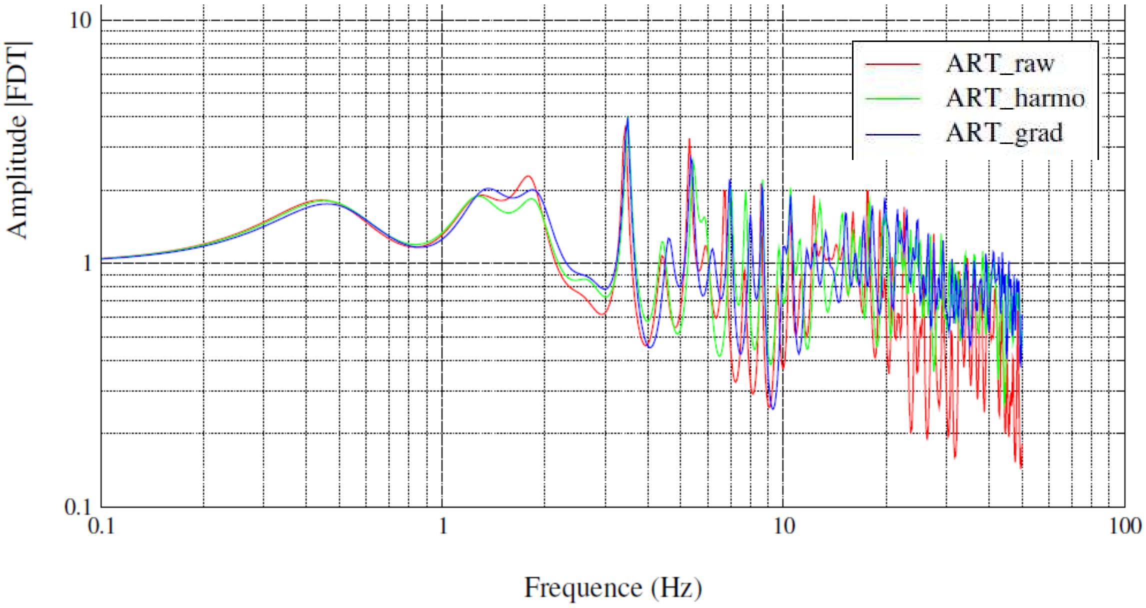

Fig. 7: same as Fig. 6 (right) for ART (without VTS) ; soil profiles are given in Fig.3

5.3 Influence of regional variability

In order to evaluate the variability of amplification induced by the regional variability of the deep layers (thicknesses of geological formations, velocity trends, ..), the horizontal transfer functions of the 5 boreholes is compared on Fig. 8.

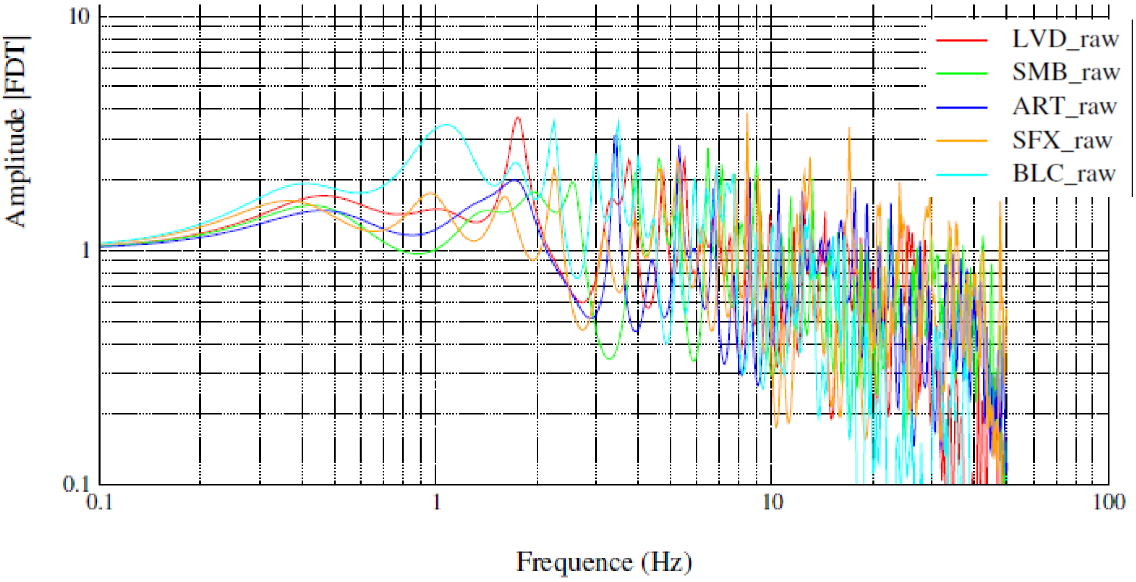

Fig. 8: Horizontal transfer function for the 5 boreholes with _raw profiles

5.4 Influence of local variability on aleatory part

In order to study the influence of local variations in the Vs profile, 4 random fields have been generated using Code_Aster [7] with the input data (log standard deviation b and correlation length Lc) provided by the statistical analysis of LVD profile, see Fig 4.

A comparison between the 4 random profiles and the _raw profile is given on Fig. 9.

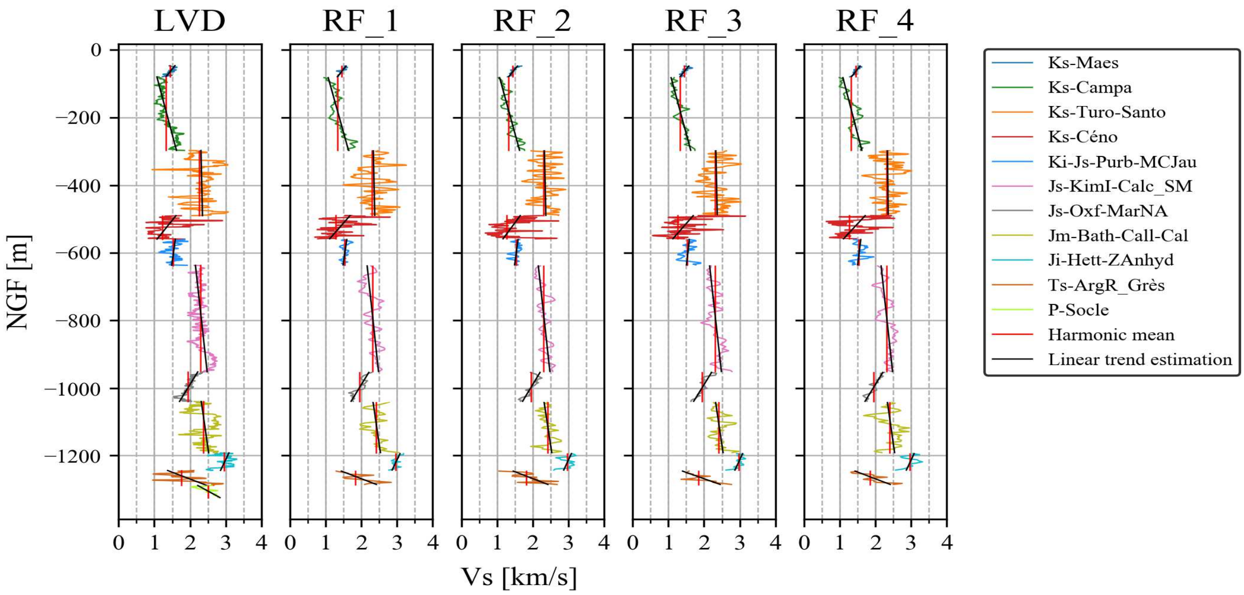

Fig. 9 : Example of 4 random field generated with *Code_Aster*, using β and Lc coefficient of Fig. 4 (left)

The horizontal transfer functions for the 4 aleatory LVD profiles of Fig. 5 are given on Fig. 10. The influence of β and Lc is visible at frequencies > 3Hz but has no influence below. High frequency scattering is well reproduced.

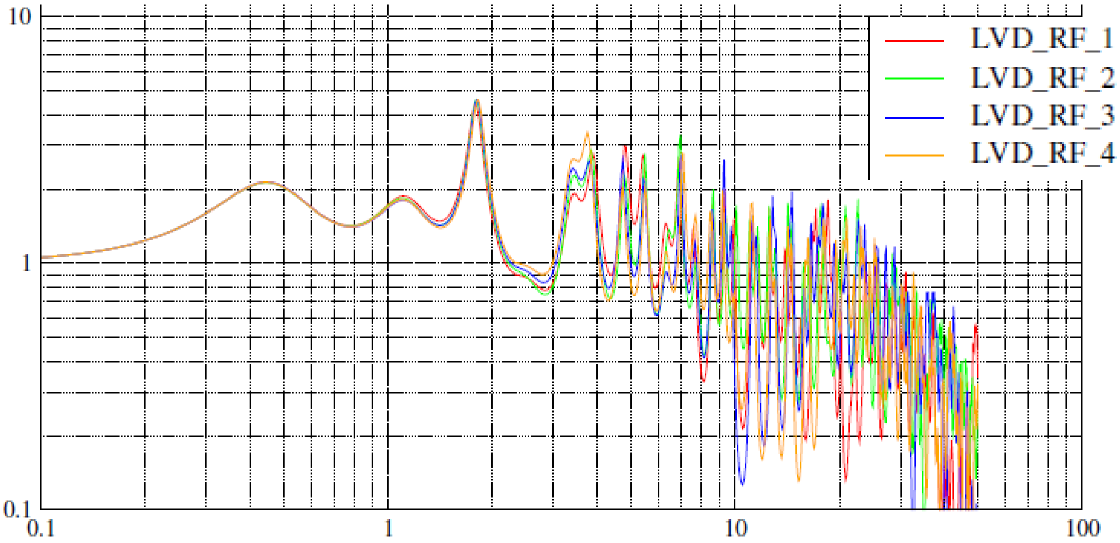

Fig. 10: Horizontal transfer function for 4 aleatory profiles generated on LVD_grad (effect of β and Lc)

5.5 Influence of local variability on trends

For LVD borehole, 20 soil profiles have been generated by varying the coefficients a and b from Eq.(13), using a normal distribution standard deviation of 0.2*a and 0.02*b respectively. The 20 Vs profiles are plotted on Fig. 11 (left). The corresponding transfer function are given in Fig. 11 (right).

The variability on trends produce an enlargement of the transfer function on the whole frequency range.

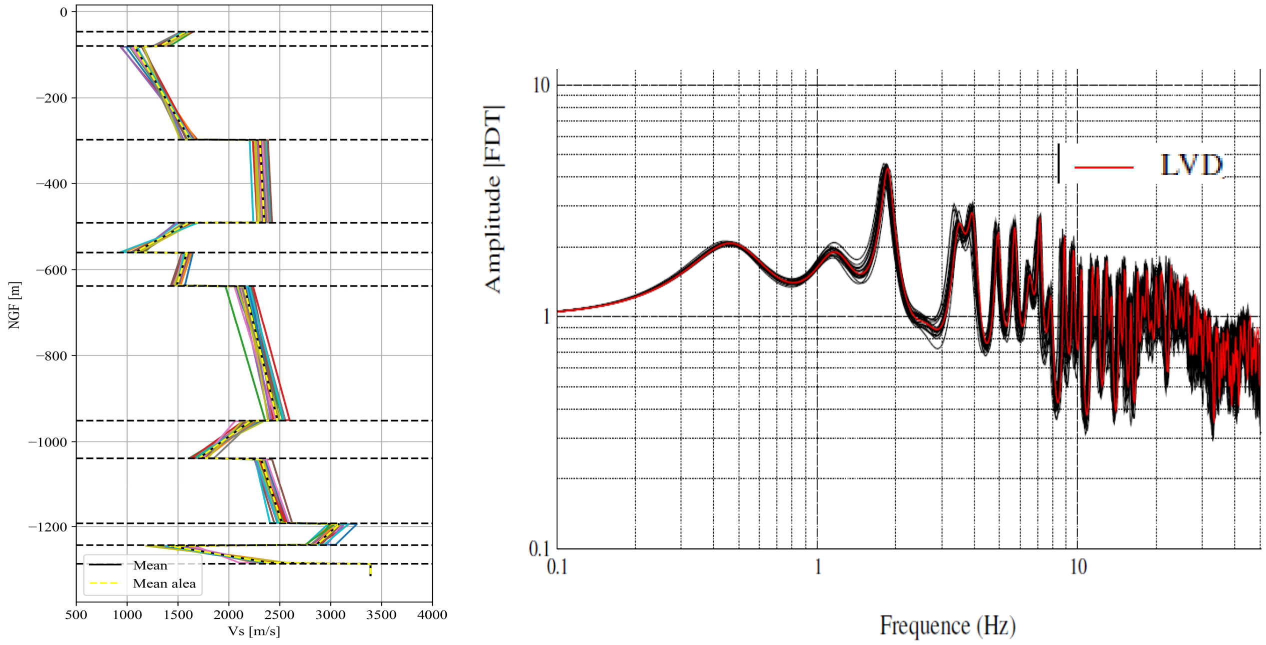

Fig.11 : 20 Vs profiles (left) for LVD generated with variability on trends (a coefficient of Eq. 13) and associated horizontal transfer function (right). The red curve is obtained with LVD_grad (mean profile)

5.6 Influence of Tertiary and Quaternary layers

In order to evaluate the impact of the deep layers amplification on a complete soil column, including subsurface layers of tertiary and Quaternary geological age, a 185m synthetic deep soil profile has been generated (named SYN). The Vs velocity is increasing from 250 m/s at the surface to 527 m/s at 164m depth, then a Top of Cretaceous transition zone is defined from 164m to 185m with Vs increasing from 1000 to 1300 m/s. This last Vs value is assumed to be representative of the engineering bedrock.

The horizontal transfer function of SYN, LVD and SYN+LVD (obtained by concatenation of SYN and LVD) are displayed on Fig. 12.

The influence of LVD layers is clearly visible on SYN+LVD transfer function: the low frequencies (<8Hz) are more amplified at the corresponding resonance frequencies of LVD, the high frequencies (>8Hz) are deamplified due to Vs scattering in the substratum.

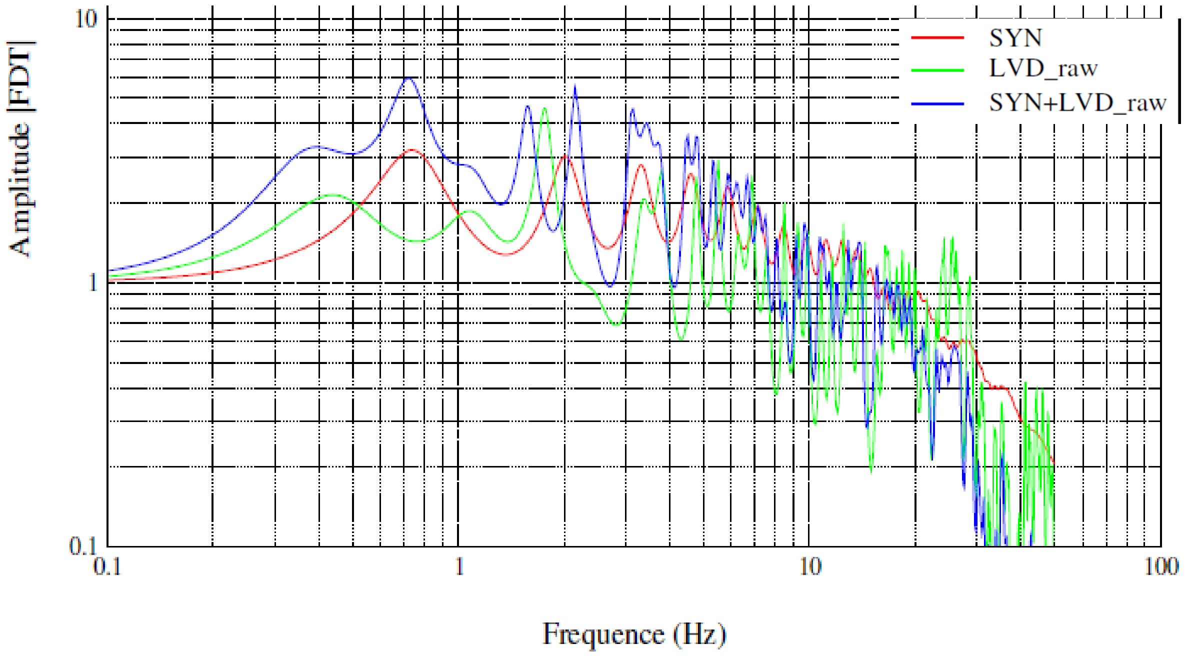

Fig.12 : Horizontal transfer function of SYN, LVD_raw and SYN+LVD_raw soil column

6. Conclusions and perspectives

This study pointed out the following results:

Sonic log from historical oil and gaz exploration boreholes can provide very precise Vp (and Vs by correlations) profiles, even if the first hundredth of meters are often missing, down to the seismological bedrock (Paleozoic formation)

The velocity profile of the soil between the engineering bedrock and the seismological bedrock is not always constant or gently increasing but shows velocities contrasts that can produce moderate amplifications at some resonance frequencies in the frequency range of seismic interest (0.1-35 Hz).

Variability on the 1D transfer function can be simulated in a satisfying manner with a simplified mean velocity profile based on an appropriate geological sublayering. Aleatory variability based on lognormal coefficient of variation and correlation length only modifies the high frequency content. Variability on the mean value and the trend of each layer can enlarge the mean transfer function on the whole frequency range.

Based on those numerical results, the following perspectives can be proposed:

The “sonic” boreholes should be a preferential location for temporary or permanent seismograph network installation, in order to try to correlate the frequency content of recorded signal with the numerical transfer function from the seismological bedrock. Indeed, this frequency content should be visible on H/V ratios (noise and earthquake) and on site-term from Generalized Inversion Technique (GIT).

2D numerical calculations can also be performed in the same way, in order to characterize the influence of dip and thickness of the layer, as well as horizontal correlation length, on horizontal transfer function.

7. References

[1] Kawase H, Nagashima F (2018): Joint inversion of H/V and surface-to-borehole ratios to obtain S-wave velocity structure and damping, *16th European Conference on Earthquake Engineering*, Thessaloniki, Greece.

[2] Mavko G, Mukerji T, Dvorkin J (1998*): The rock physics handbook: Tools for seismic analysis in porous media.* Cambridge Univ. Press.

[3] Castagna JP, Batzle ML, Eastwood RL (1985): Relationships between compressional-wave and shear-wave velocities in elastic silicate rocks, *Geophysics,* vol. 50, no. 4, p. 571-581

[4] Brocher T (2007): Key elements of regional seismic velocity models for long period ground motion simulations, *Journal of Seismology · April 2007*

[5] Gardner G, Gardner L, Gregory A (1974): Formation velocity and density – the diagnostic basics for stratigraphic traps. *Geophysics*, *39*(*6*): 770–780

[6] Zentner I, Devesa G, Vandeputte D (2018): Stochastic models to represent soil spatial variability, implementation in FEM software, and impact on dynamic response of structures, *16th European Conference on Earthquake Engineering*, Thessaloniki, Greece

[7] *Code_Aster* : Finite Element Method opensource software : *www.code-aster.org*

[8] Sato H, Yamanaka H (2011): Site response estimation by 1D heterogeneous velocity model using borehole log and its relationship to damping factor. *4th IASPEI/IAEE International Symposium : Effects of Surface Geology on Seismic Motion, August 23-26, 2011, UCSB*