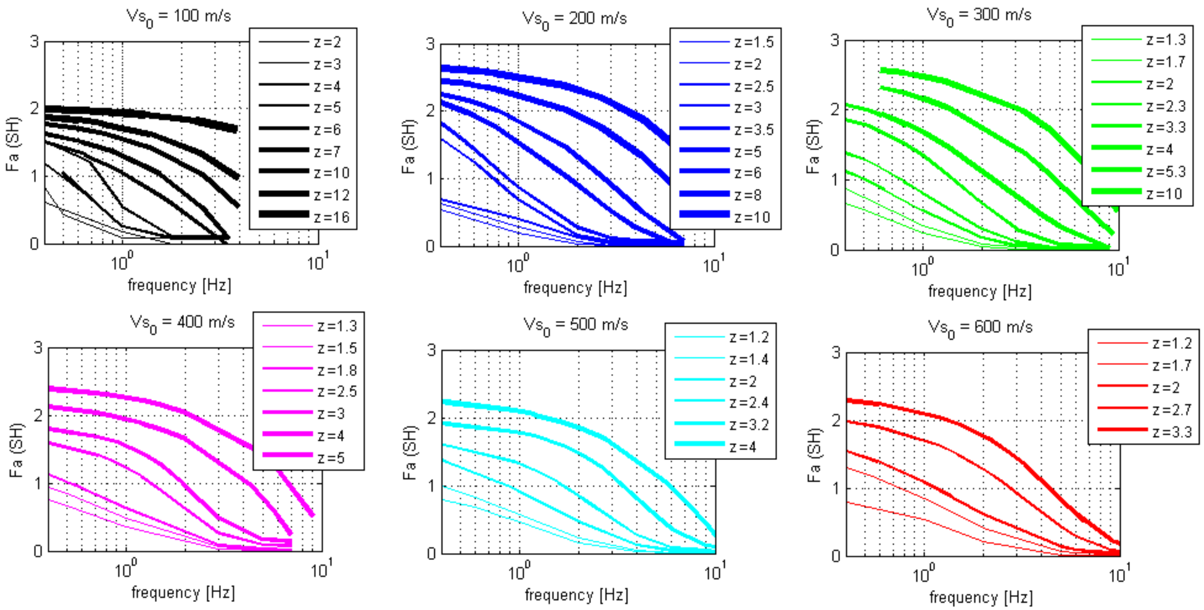

THE VFZ MATRIX:
SIMPLIFIED SEISMIC SOIL CLASSIFICATION FROM A DIFFERENT PERSPECTIVE

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In the recent days we saw several examples of highly detailed site response calculations.

In principle, these offer a superior accuracy.

However, they require a knowledge of the relevant parameters which is hardly realized in daily practice.

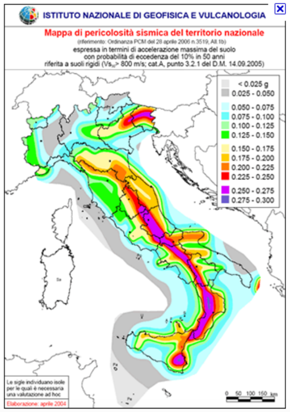
Acknowledging this, we look for a simplified - yet as physically meaningful al possible - method, which has to be practically and widely applicable.

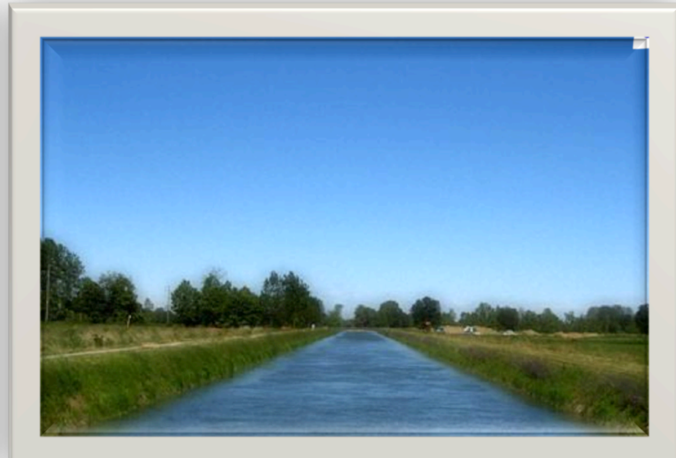
→ We deal only with stratigraphic amplification (liquefaction, topographic effects etc. are beyond our interest here) ←

THE WHOLE ITALIAN TERRITORY IS CONSIDERED TO BE SEISMICALLY ACTIVE, THEREFORE SITE RESPONSE ANALYSES ARE REQUIRED **by law**

- AT ALL SITES

- FOR ALL STRUCTURES



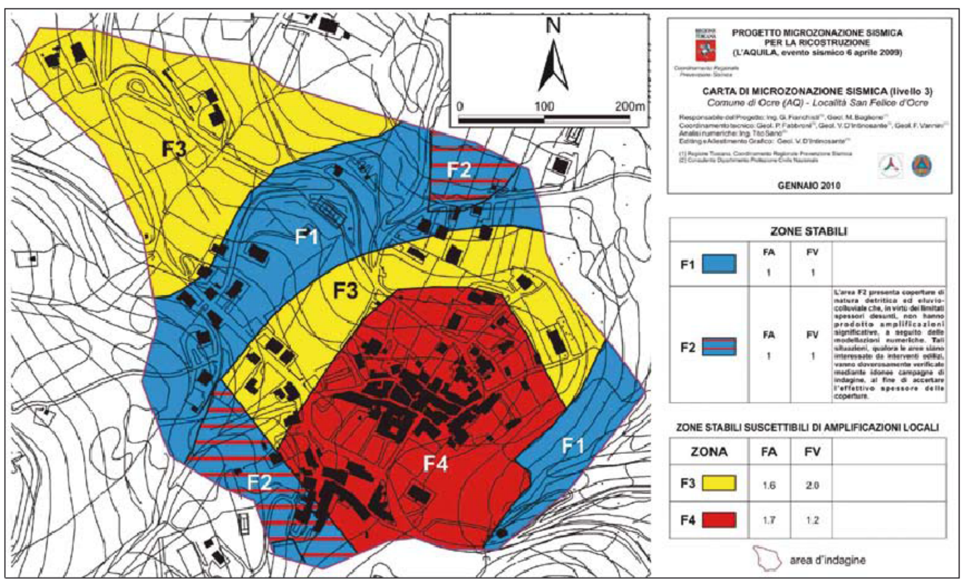


SEISMIC SITE EFFECTS ASSESSMENT CAN BE CONDUCTED AT 2 LEVELS

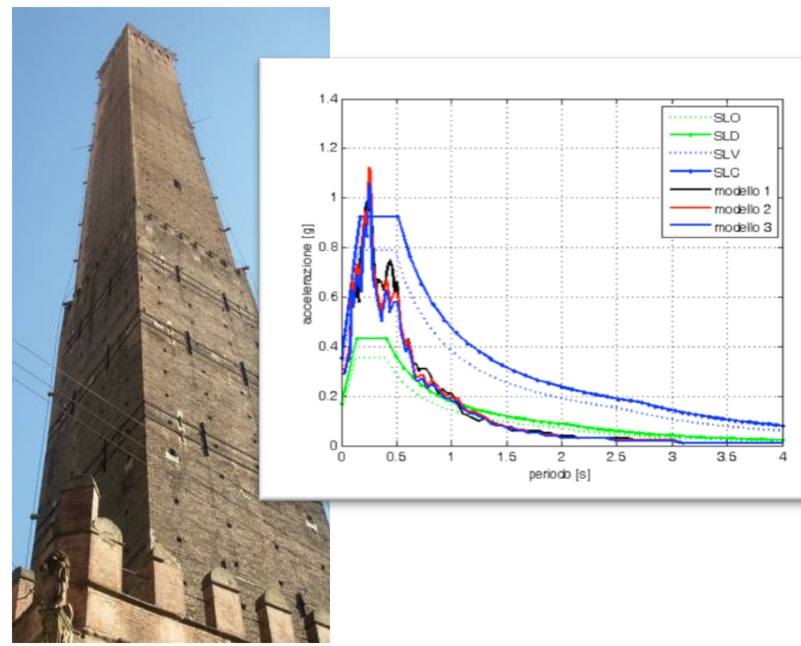
MID- TO LARGE-SCALE:
shake maps, urban planning

SMALL SCALE:
single construction

SEISMIC MICROZONATION



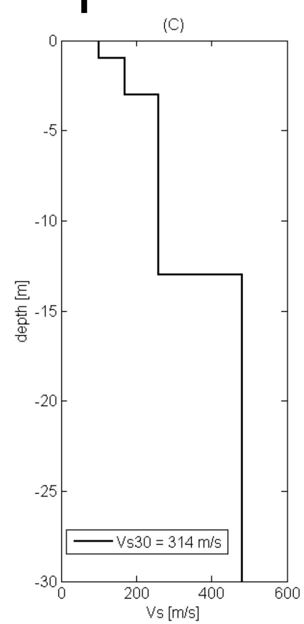
BUILDING CODES



SEISMIC SITE RESPONSE STUDIES ARE BASED ON

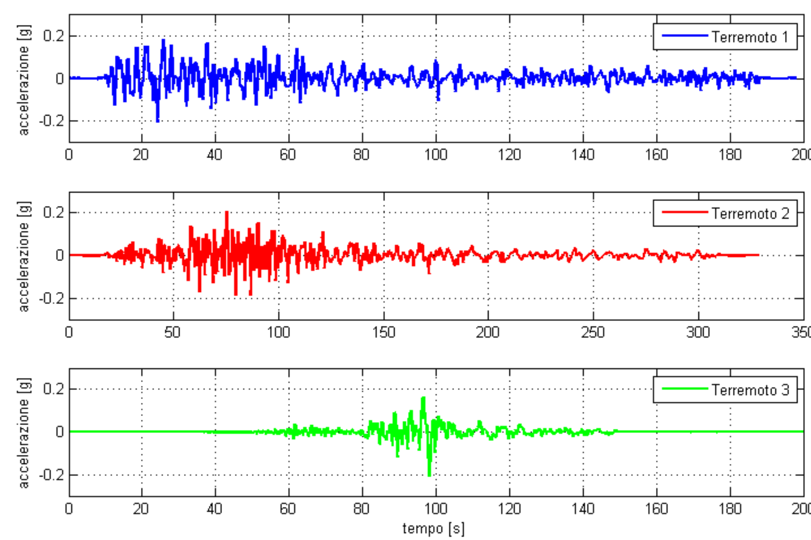
INPUT 1: MECHANICAL PROPERTIES OF THE SUBSOIL

- Vs, ρ profile
- depth of the water table
- shear modulus dependance with strain
- etc.



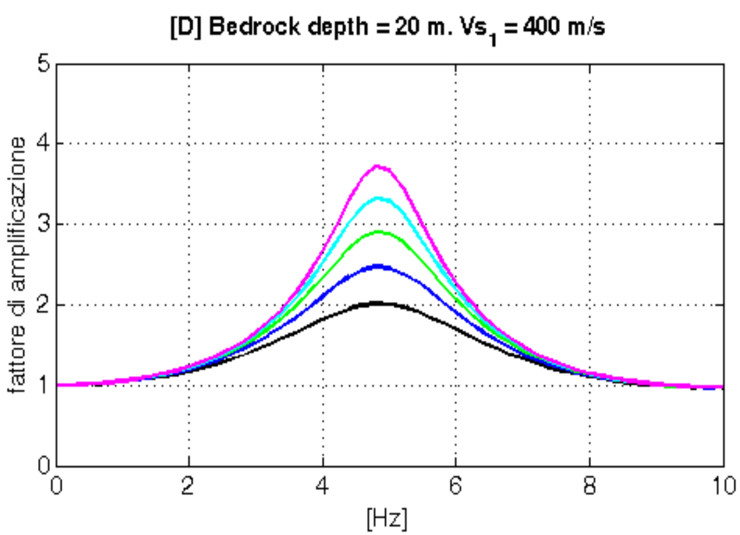
INPUT 2: GROUND MOTION

- "characteristic" earthquake
  (typical PGA_0 expected at the bedrock, typical durations, typical waveforms etc.)



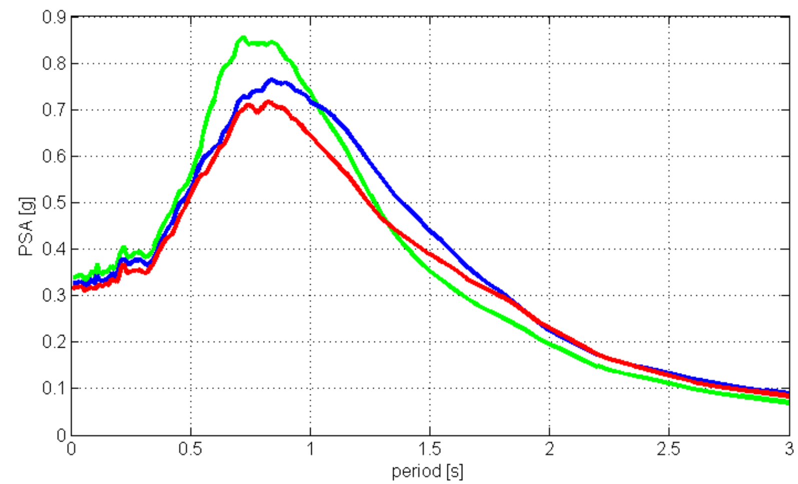
AND SHOULD PROVIDE

OUTPUT 1:
BEDROCK → SURFACE TRANSFER FUNCTION



THIS DEPENDS ON THE SOIL PROPERTIES

OUTPUT 2:
RESPONSE SPECTRUM



The maximum accleration/velocity/displacement expected on a single degree of freedom oscillator (building) for a specified damping and eigen-period

THIS DEPENDS STRONGLY ON THE SPECIFIC INPUT MOTION

ALL INPUT VARIABLES HAVE INTRINSIC UNCERTAINTIES. IS THIS ACKNOWLEDGED AND CORRECTLY CONSIDERED? (1)

$$\sigma_{log(PGA0)} > 0.2$$

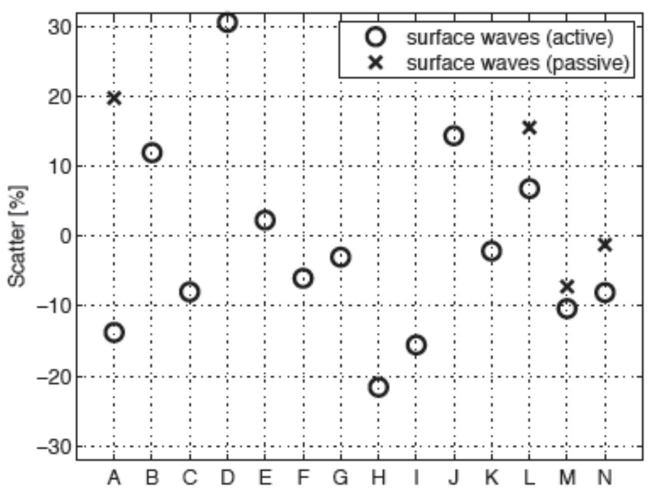
Typical uncertainty in the logarithm of PGA_0 (Campbell, 1981; Boore et al., 1993, etc.). The uncertainty on PGA_0 is therefore $10^{0.2}$ or $e^{0.2}$, that is 1.6 or 1.2 g

			T_R=30			T_R=50		
ID	LON	LAT	a_g	F_o	T_C^*	a_g	F_o	T_C^*
13111	6.5448	45.134	0.263	2.50	0.18	0.340	2.51	0.21
13333	6.5506	45.085	0.264	2.49	0.18	0.341	2.51	0.21
13555	6.5564	45.035	0.264	2.50	0.18	0.340	2.51	0.20

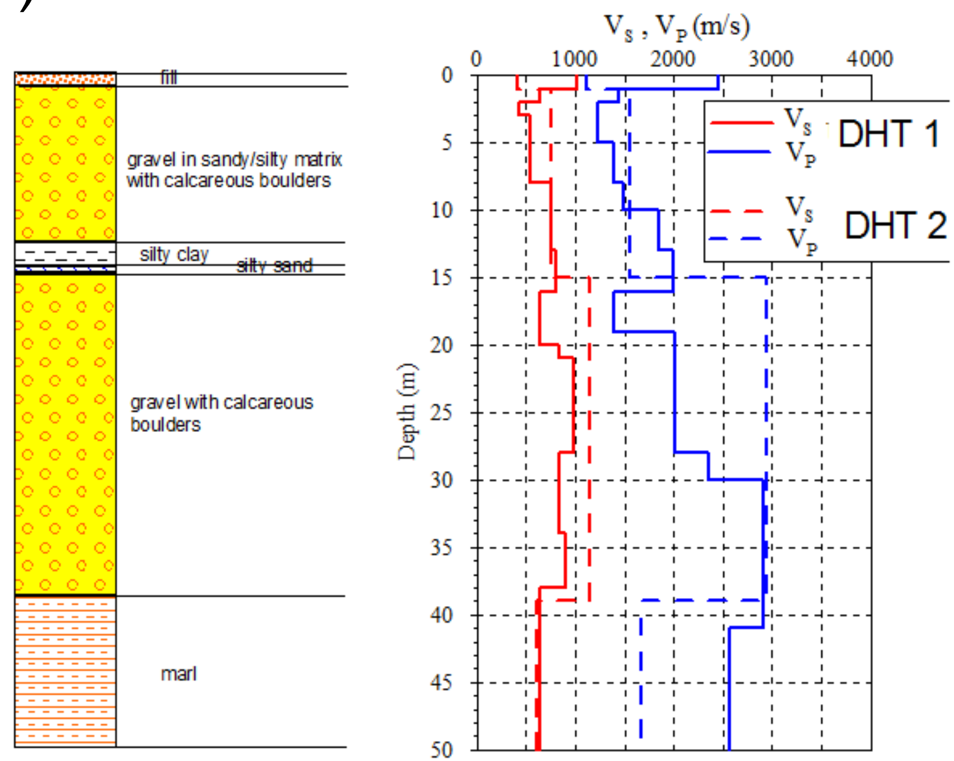
The use of 3 significant digits for PGA_0 is meaningless (Italian Building Code, 2008. But it is not the only one).

ALL INPUT VARIABLES HAVE INTRINSIC UNCERTAINTIES. IS THIS ACKNOWLEDGED AND CORRECTLY CONSIDERED? (2)

- Errors associated to the estimate of the Vs profiles are, to be optimistic, of the order of 20% (Asten and Boore, 2005; Mulargia and Castellaro, 2009)

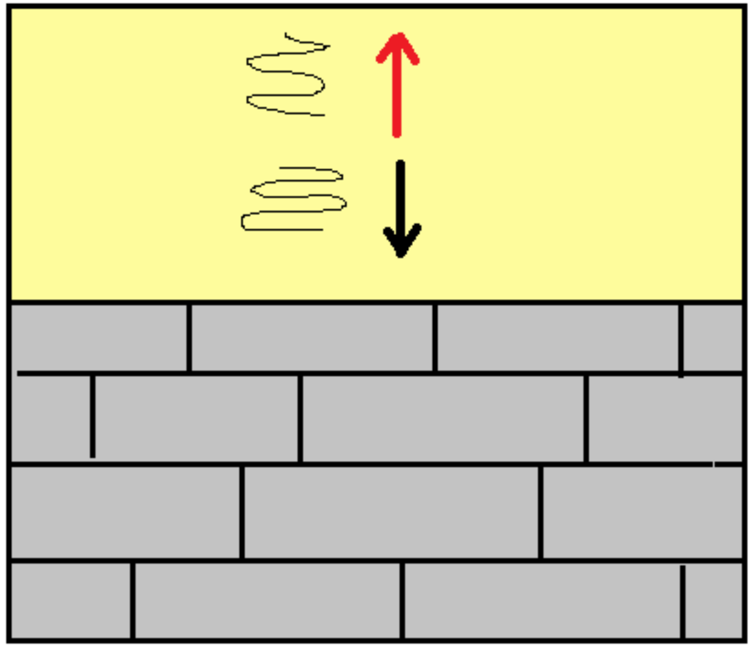


▲ **Figure 1.** Percentage scatter between *Vs*30 estimates at different sites. The *Vs*30 value obtained from direct methods (borehole) is used as a reference to compare *Vs*30 from surface methods (circles for passive methods, crosses for active methods). A) data presented in Louie (2001), B) data presented in Williams *et al.* (2003) for site FOS, C) ibid. for site SOW, D) ibid. for site KIN, E) ibid. for site SOP, F) Brown *et al.* (2002) for site CERRI-TOS, G) ibid. for site GARNER, H) ibid. for site JENSEN, I) ibid. for site OBREGON, J) ibid. for site POTRERO, K) ibid. for site RINALDI, L) Stephenson *et al.* (2005) for site CCOC, M) ibid. for site MGCY, N) ibid. for site STGA.



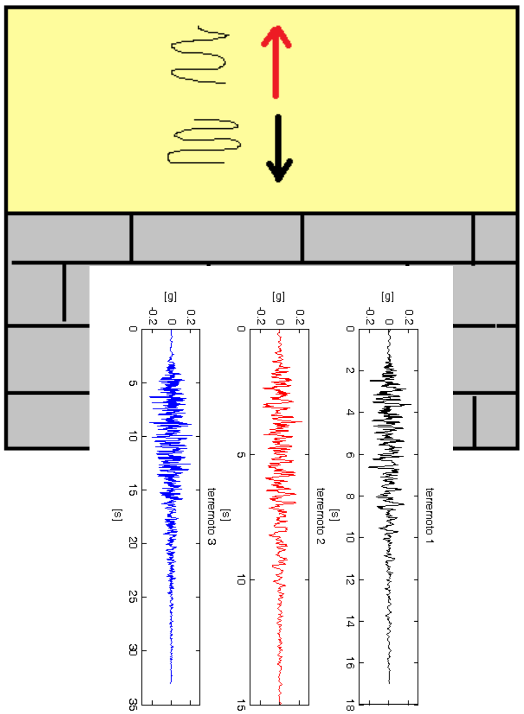
DH effected in the same hole by 2 teams belonging to 2 different universities. Differences larger than 100% are evident.

ALL INPUT VARIABLES HAVE INTRINSIC UNCERTAINTIES. IS THIS ACKNOWLEDGED AND CORRECTLY CONSIDERED? (3)



Standard codes used to infer the SH-amplification factor and response spectrum rely on a normally incident, horizontally polarized, moving upward-downward SH wave

ALL INPUT VARIABLES HAVE INTRINSIC UNCERTAINTIES. IS THIS ACKNOWLEDGED AND CORRECTLY CONSIDERED? (3)

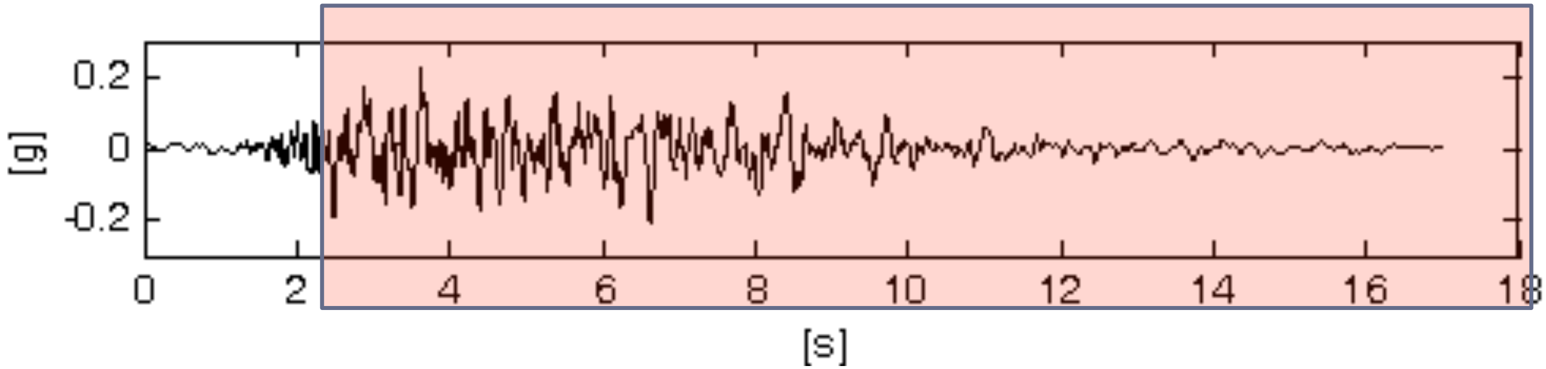


But the Eurocodes ask the user to input at least 7 full accelerograms

ALL INPUT VARIABLES HAVE INTRINSIC UNCERTAINTIES. IS THIS ACKNOWLEDGED AND CORRECTLY CONSIDERED? (3)

Seismology teaches that

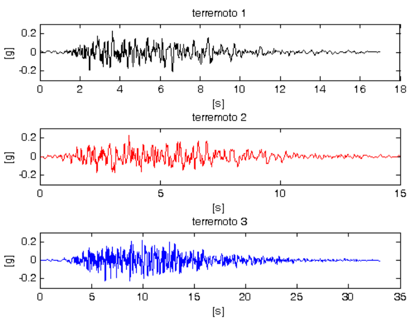
1. LOCAL AND REGIONAL EVENTS	TELESEISMIC EVENTS
1. largest amplitudes → crustal channel waves Lg and 2. for near surface sources → short period fundamental Rayleigh mode Rg	1. surface waves of shallow events have by far the largest amplitudes NMSOP, 2001

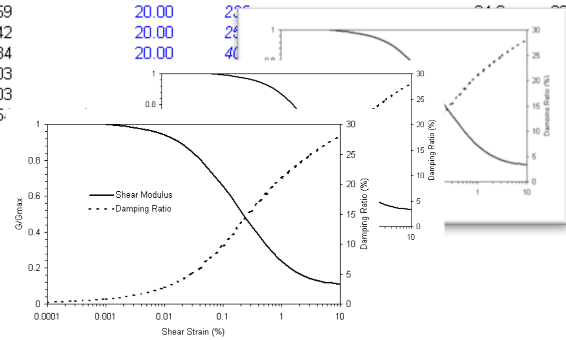


Which means that the most part of the accelerogram is *not* a SH-wave

WITH SO MANY INPUT PARAMETERS AND ASSUMPTIONS...

Layer Number	Soil Material Type	Number of sublayers in layer	Thickness of layer (m)	Maximum shear modulus G_{max} (MPa)	Initial critical damping ratio (%)	Total unit weight (kN/m^3)	Shear wave velocity (m/sec)	Location and type of earthquake input motion	Location of water table	Depth at middle of layer (m)	Vertical effective stress (kPa)
1	1		2.5	94.24		20.00	215			1.3	25.00
2	4		4.5	91.63		20.00	212		W	4.8	95.00
3	4		1.5	98.67		20.00	220			7.8	147.64
4	4		7.3	103.21		20.00	225			12.1	192.48
5	3		3.5	123.85		22.00	235			17.5	251.00
6	4		10.7	112.59		20.00	2[illegible]			[illegible]	[illegible]6.85
				42		20.00	25				1.68
				34		20.00	40				979
				03							988
				03							966
				5.							3.72





WHAT IS THE SIGNIFICANCE OF THE OUTPUT?

A SIMPLIFIED SOIL CLASSIFICATION IS STRONGLY NEEDED IN THE GEOLOGICAL AND ENGINEERING PRATICE

AS WE ALL KNOW, A SIMPLIFIED SOIL CLASSIFICATION METHOD ALREADY EXISTS AND IS BASED ON

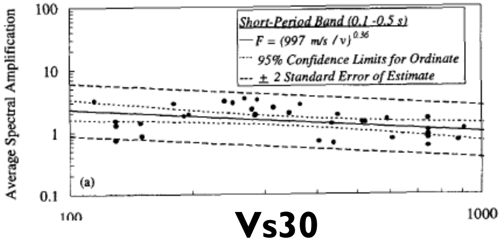
Vs30

Developed on a purely empirical basis, it has been shown to suffer from *statistical* (Castellaro et al., SRL, 2008) and *physical* problems (Lee and Trifunac, Soil Dyn. Earth. Eng. 2010).

Now we analyze it from a numerical point a view and cast the basis for an alternative approach.

RATIONALE FOR A NEW SIMPLIFIED SITE CLASSIFICATION

Castellaro et al., SRL, 2008



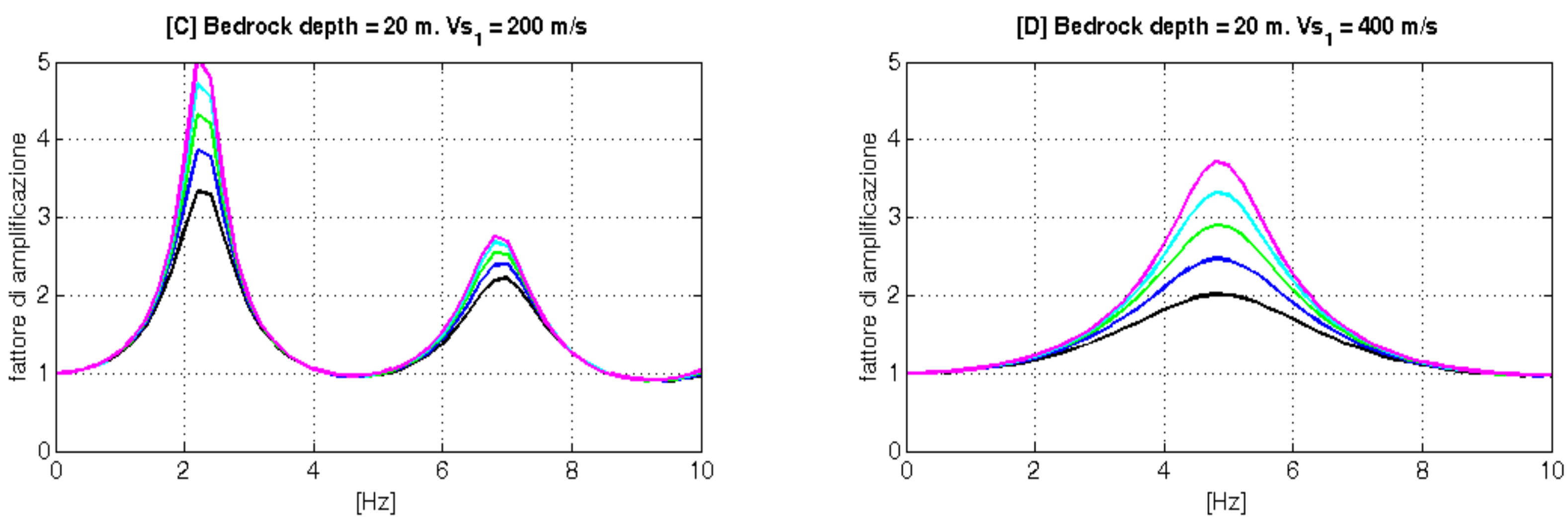
1: Vs30 does not take into account impedance contrasts, which cause the amplification

LIMITATIONS OF THE Vs30 METHOD: QUALITATIVE APPROACH (1)

- Vs is an estimator of soil stiffness

$$\mu = \rho V_s^2$$

- However, SH stratigraphic amplification is ruled by impedance contrasts, Z, not simply by absolute stiffness



Soil damping is actually an important factor but at this stage it is disreagarded

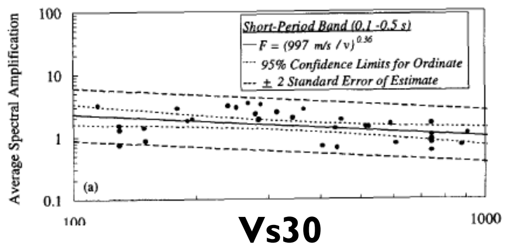
LIMITATIONS OF THE Vs30 METHOD: QUALITATIVE APPROACH (1)

- the information on the impedance contrast is lost in all site classes
- but in the E site class (EC8 / Italian classification system)

SOIL CLASS	Vs / Vs30 REQUISITES
A	Vs30 > 800 m/s
B	Gradually increasing Vs with depth 360 < Vs30 ≤ 800 m/s
C	Gradually increasing Vs with depth 180 < Vs30 ≤ 360 m/s
D	Vs30 ≤ 180 m/s
E	Bedrock (Vs > 800 m/s) at depth < 20 m Overburden Vs(0-bedrock) ≤ 360 m/s Explains only resonances above 2.3 or 4.5 Hz, depending on the Vs(0-bedrock)
S1, S2	Other cases

RATIONALE FOR A NEW SIMPLIFIED SITE CLASSIFICATION

Castellaro et al., SRL, 2008

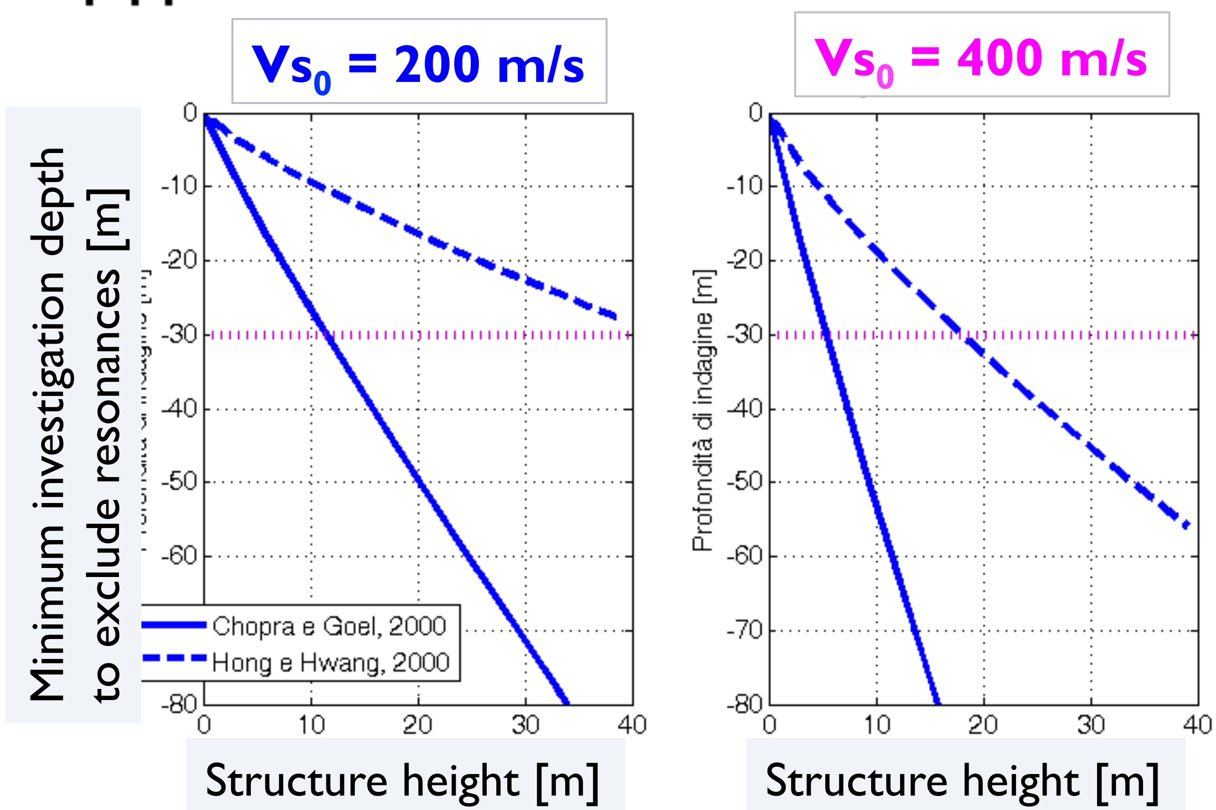


2: 30 m cannot be enough (or can be too much) to describe the amplification in the frequency range of engineering interest

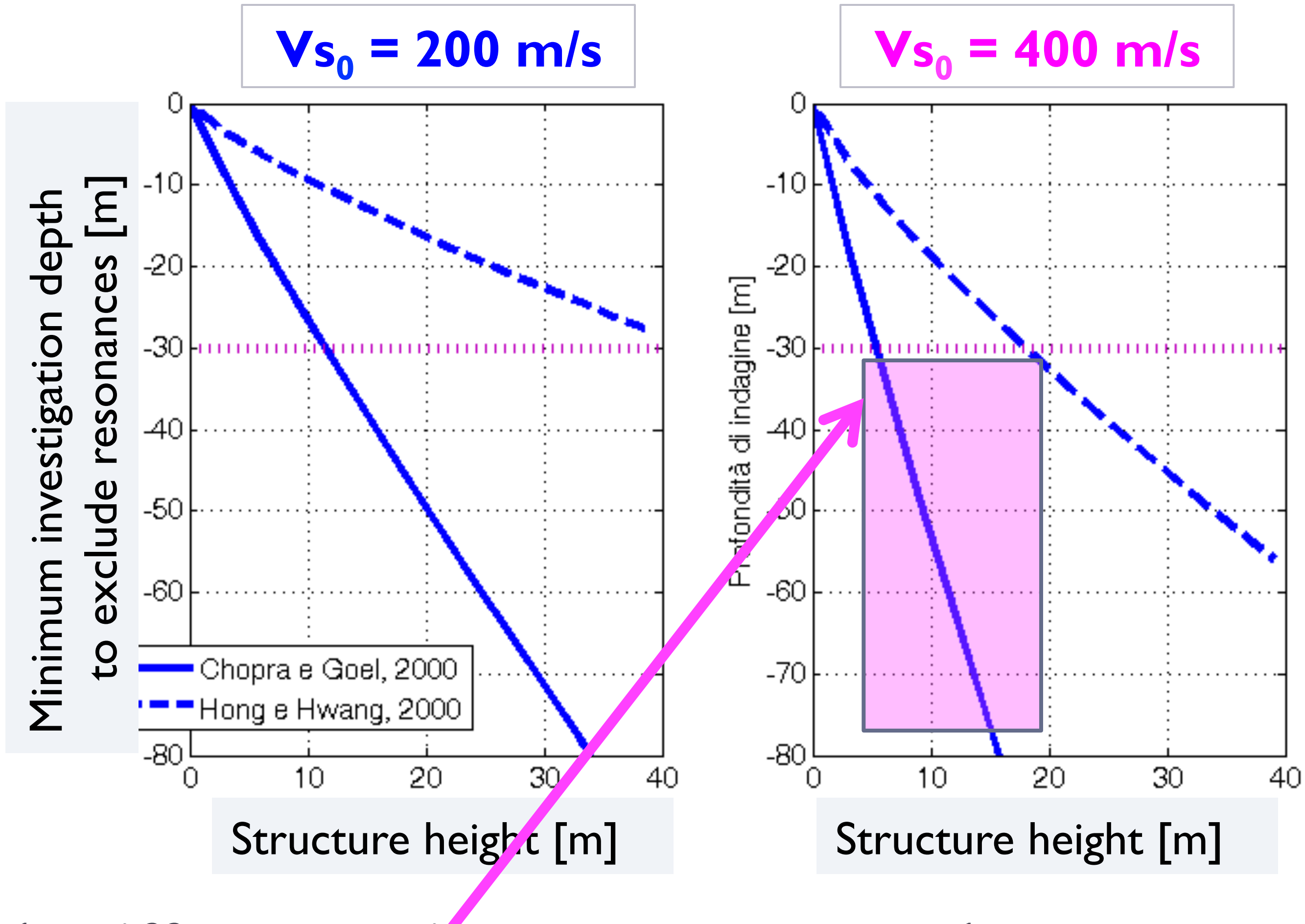
LIMITATIONS OF THE Vs30 METHOD: QUALITATIVE APPROACH (2)

Simplifying to the most…

SUBSOIL RESONACE (fundamental mode)	STRUCTURE FUNDAMENTAL PERIOD AS A FUNCTION OF HEIGHT (A)
$$f = \frac{V}{4\,H}$$	$$T = 0.0294\,A^{0.804} \qquad T = 0.067\,A^{0.9}$$



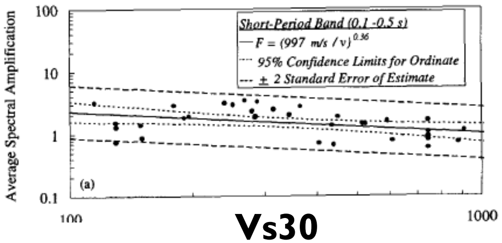
A “geotechnical paradox”: the stiffer the soil, the largest the depth of investigation needed to exclude amplification at some frequencies



On mid-stiffness soils, 30 m may be not enough to characterize resonances at frequency potentially important even for 2 -3 storey buildings

RATIONALE FOR A NEW SIMPLIFIED SITE CLASSIFICATION

Castellaro et al., SRL, 2008



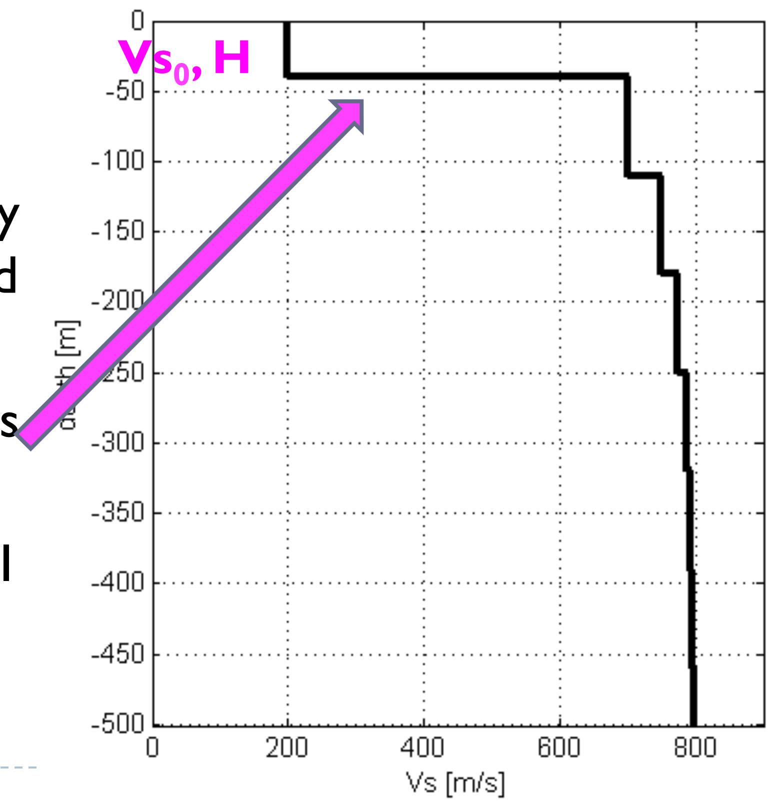
1: Vs30 does not take into account impedance contrasts, which cause the stratigraphic amplification

2: 30 m cannot be enough (or can be too much) to describe the amplification in the frequency range of engineering interest

3: several combinations of stiffness-thickness may result in different Vs30 (i.e. different soil classes) but substantially in the same amplification function and vice-versa

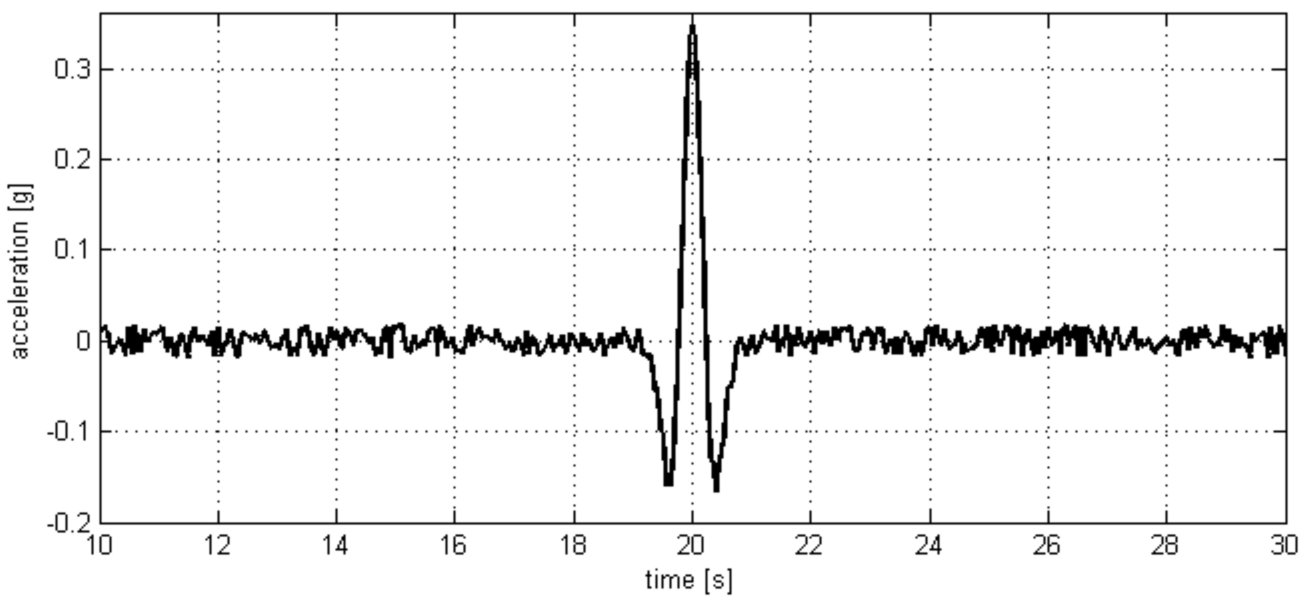
MODELING

- To investigate the relevance of the impedance contrasts, rather than the absolute velocity in the first 30 m depth, to the amplification function expected at a site, we study a dataset of subsoils with the following properties:
- *Layer 1:* Vs_0 = [100, 600] m/s, thickness H = [3, 300] m,
- *Layer 2:* Vs > Vs_0, Vs = [200, 2000] m/s,
- *Layer 3 to 30:* Vs increases in a exponentially decaying way down to the bedrock, located at 2 km depth.
- The maximum impedance contrast Z is between layer 1 and layer 2.
- 45 different Vs profiles for each layer 1 thickness
- 585 subsoil models investigated



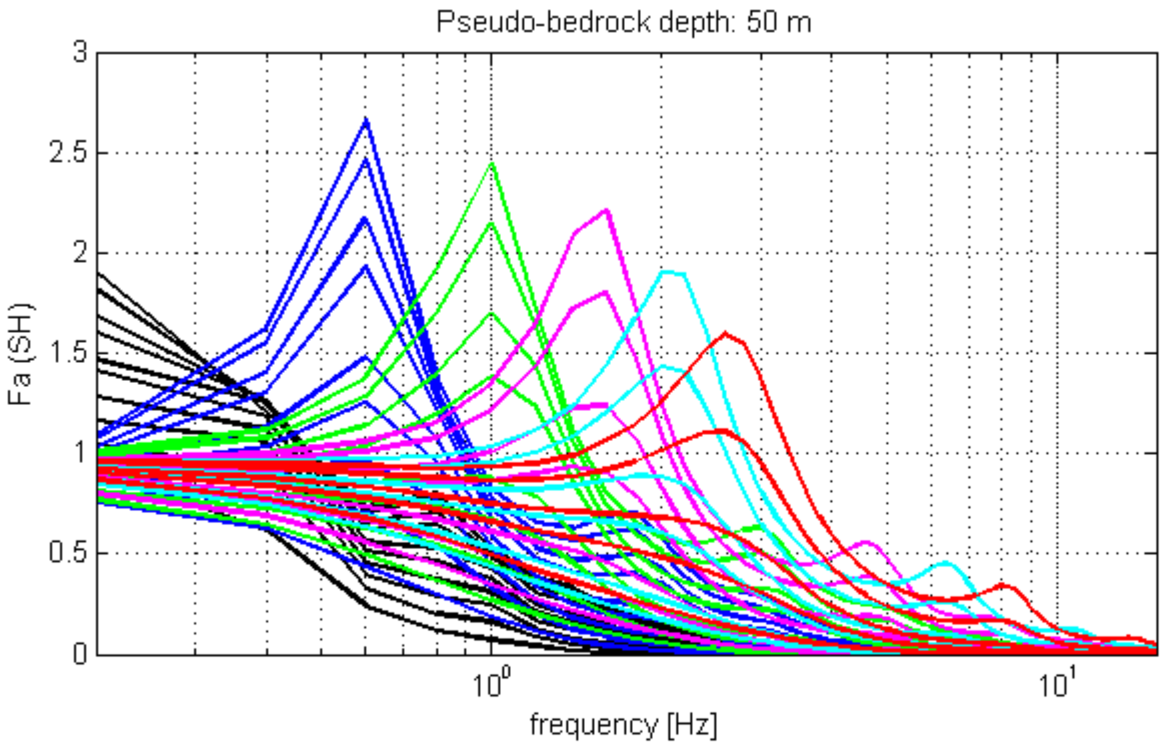
MODELING

- To reduce the number of variables and to better analyze their influence, we keep the input motion function (the earthquake) as simple as possible. The earthquake motion is therefore a Ricker wavelet with frequency of 1 Hz and 0.5 Hz, in order to simulate intermediate-small and intermediate-large earthquakes, respectively



MODELING

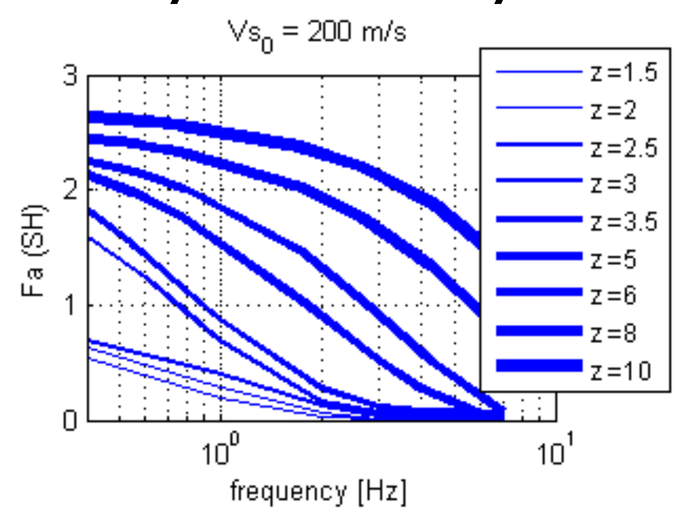
- We run the 1D equivalent-linear site response simulations for the 585 models



Amplification functions obtained from the 45 models with layer 1 thickness = 50 m

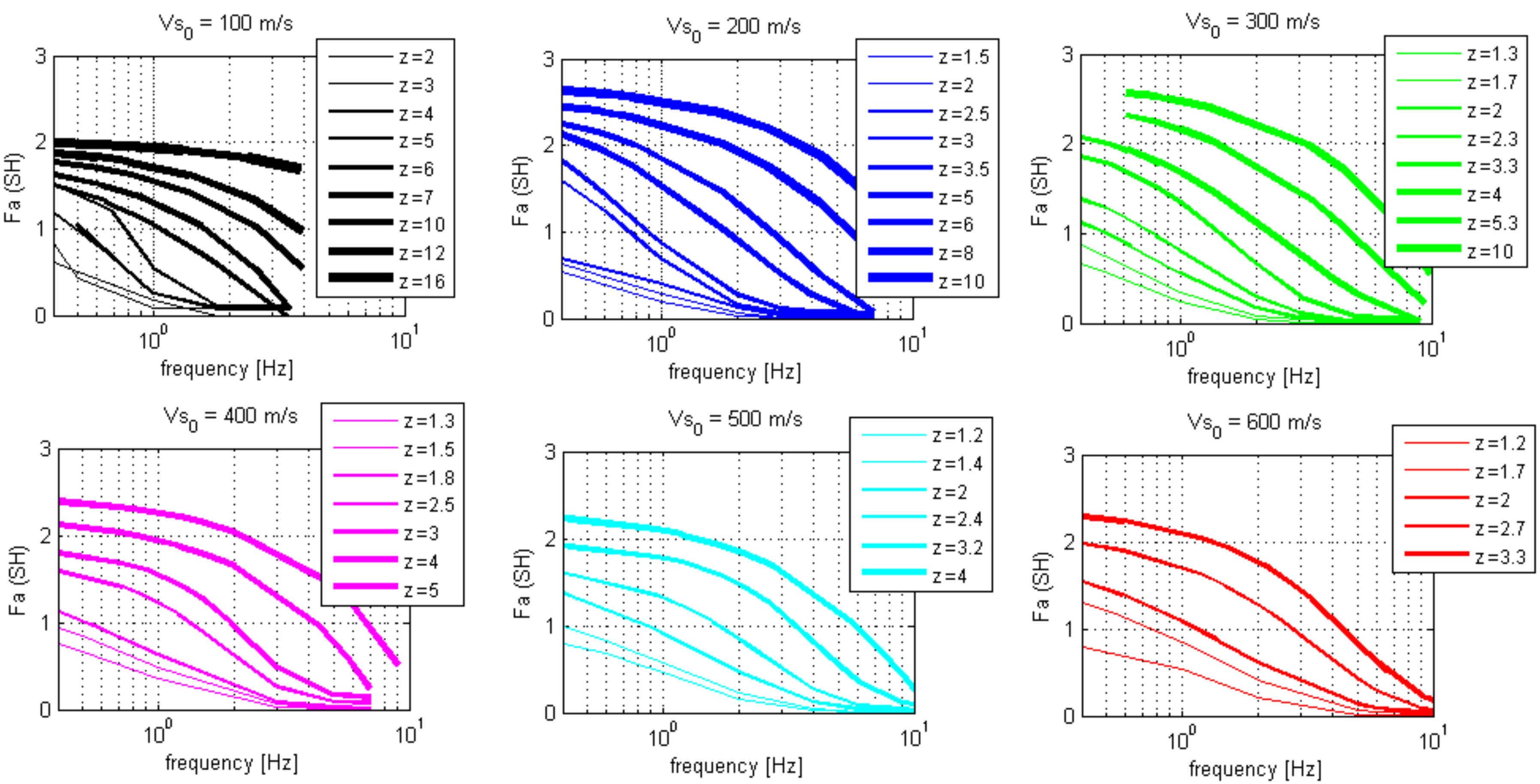
MODELING: THE VFZ MATRIX

- For each tested Vs_0 we plot the maximum amplification as a function of its frequency of occurrence, which depends on the bedrock depth and obtain a plot like the one shown in the figure below.
- Each line in this plot connects the points characterized by the same impedance contrast between layer 1 and layer 2.
- These plots therefore represent a way to get a quick estimate of the expected SH amplification factor, from (Vs_0, f_0, Z).



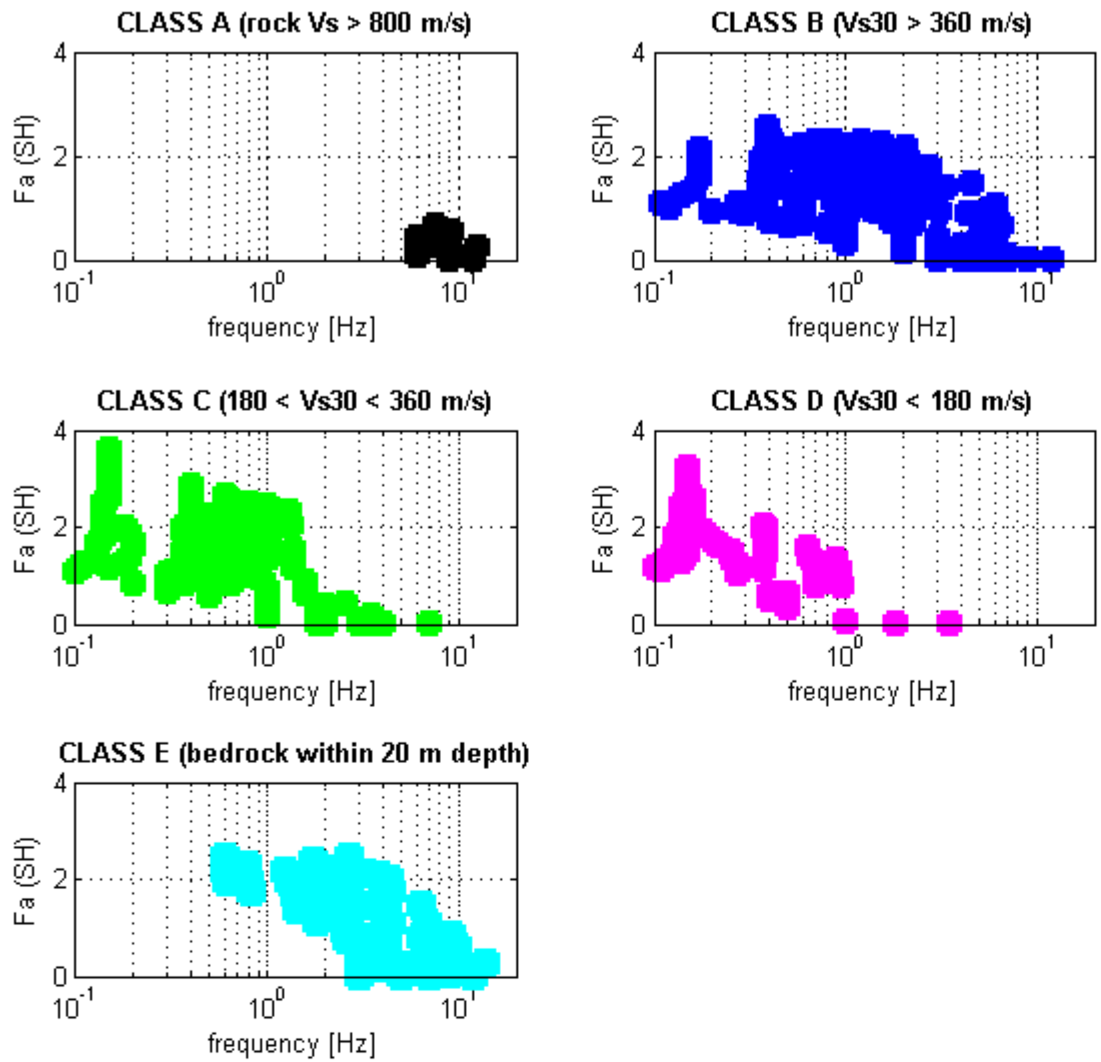
THE VFZ MATRIX

- Vs_0, f_0 and Z are the basic parameters of our classification scheme (Fa_{SH} proxy)



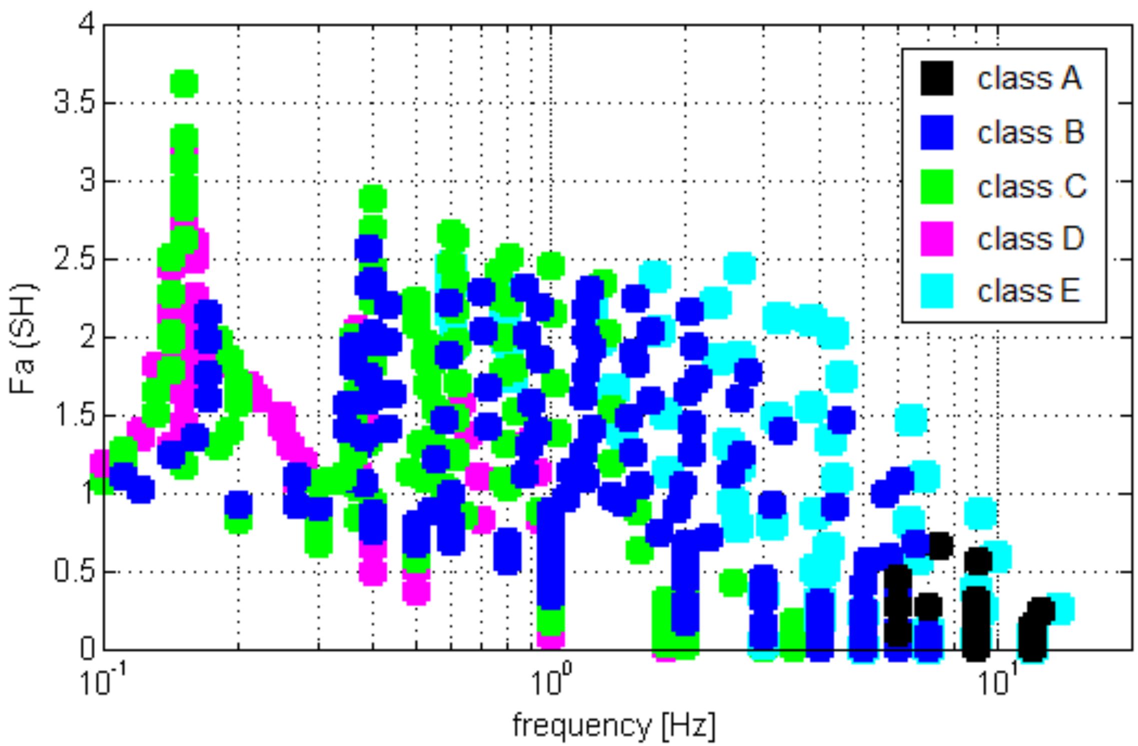
LIMITATIONS OF THE Vs30 METHOD: QUANTITATIVE APPROACH (1)

- We group the maximum amplification and frequency of occurrence of our models according to their Vs30 site class.
- Vs30 cannot effectively discriminate neither different soil amplifications, nor different amplification frequencies.



LIMITATIONS OF THE Vs30 METHOD: QUANTITATIVE APPROACH (1)

Vs30 cannot effectively discriminate neither different soil amplifications, nor different amplification frequencies.

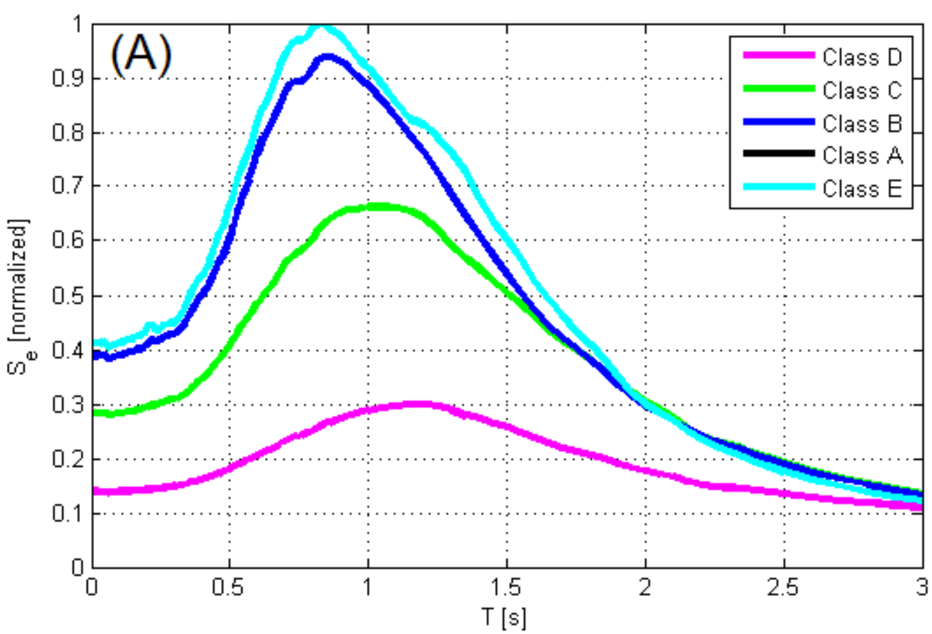


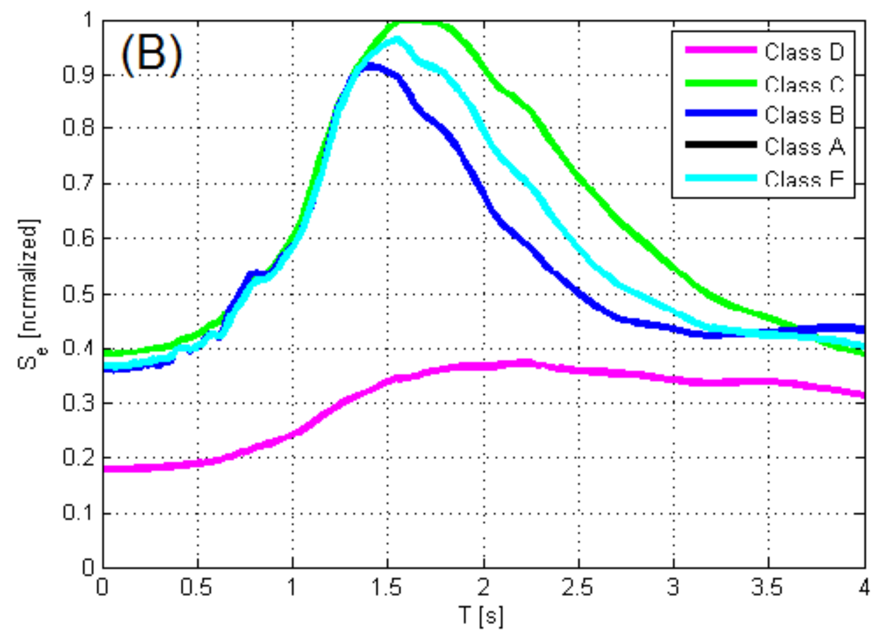
LIMITATIONS OF THE Vs30 METHOD: QUANTITATIVE APPROACH (2)

Average response spectra derived from our models for each Vs30 site class.

Input: 1 Hz Ricker wavelet (left). The highest accelerations are expected for buildings on soil classes E and B and there is a general shift of the frequency of the maximum amplification, which decreases from site E to B to C and D.

Input: 0.5 Hz Ricker wavelet (right). The maximum is found on class C sites and the frequency of the maximum increases from site C to E to B.

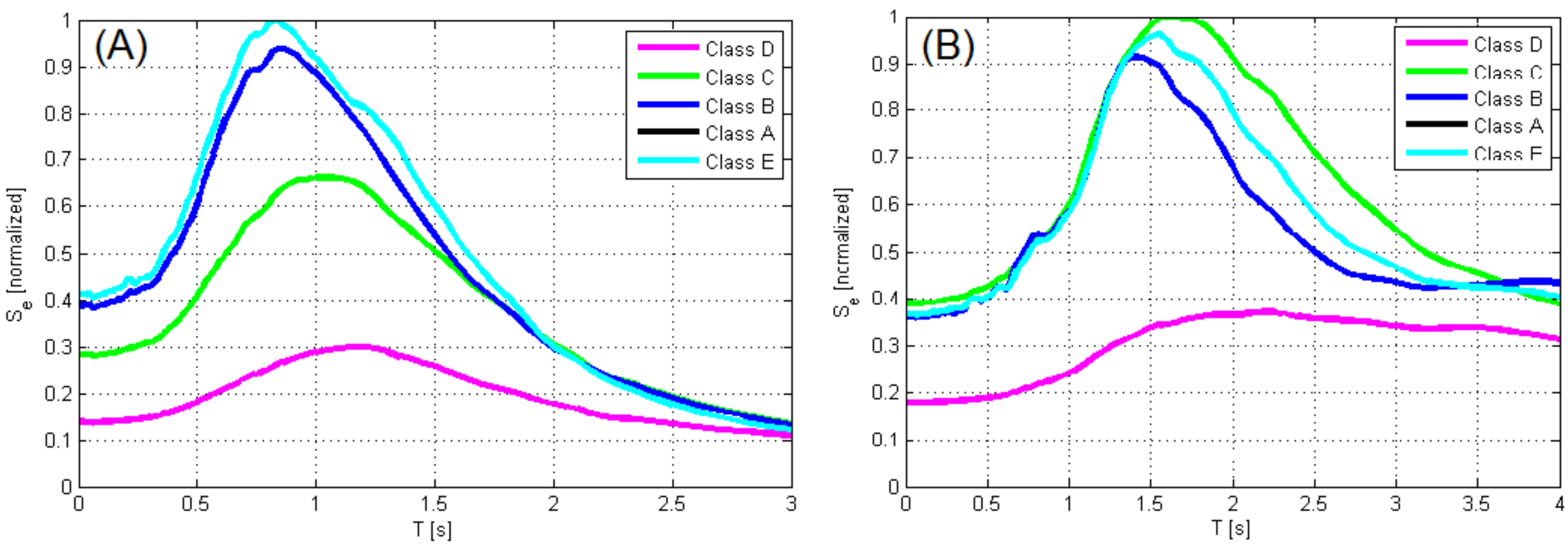




LIMITATIONS OF THE Vs30 METHOD: QUANTITATIVE APPROACH (2)

Average response spectra derived from our models for each Vs30 site class.

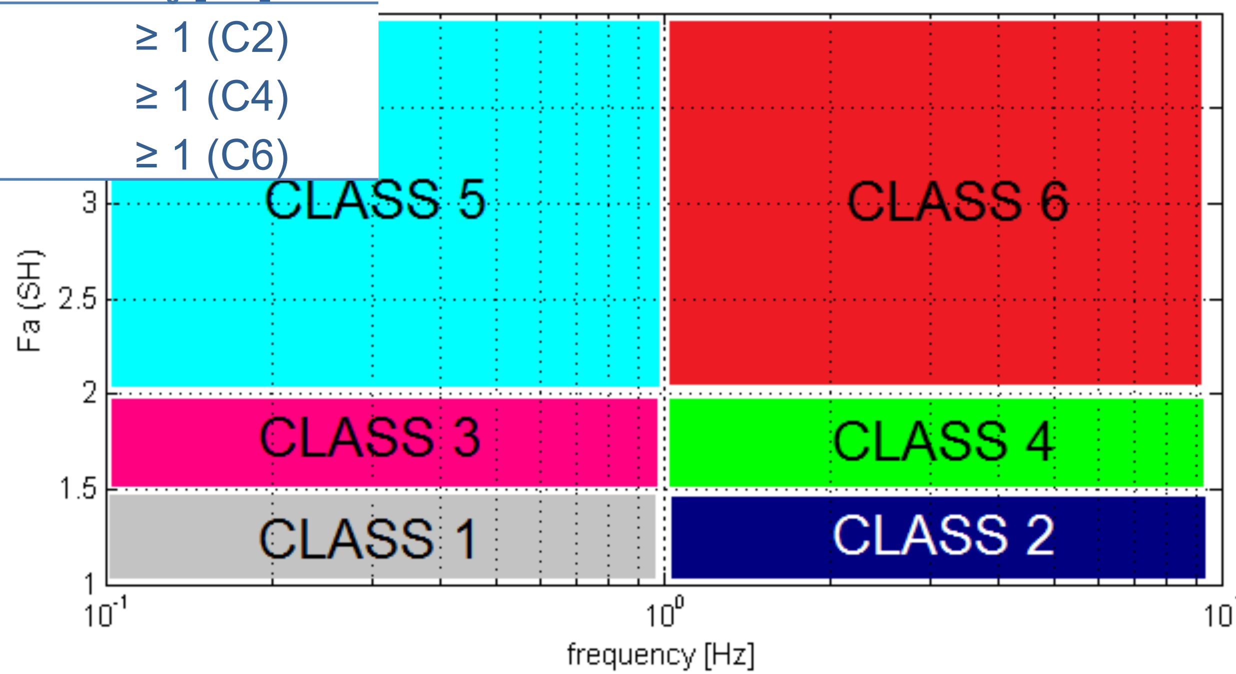
The Vs30 parameter is not a good proxy to seismic site classification also when response spectra are considered, since the latter are very sensitive to the specific frequency content of the input motion compared to the subsoil eigen-frequency, which is not taken into account by the Vs30 approach.



THE VFZ MATIRX

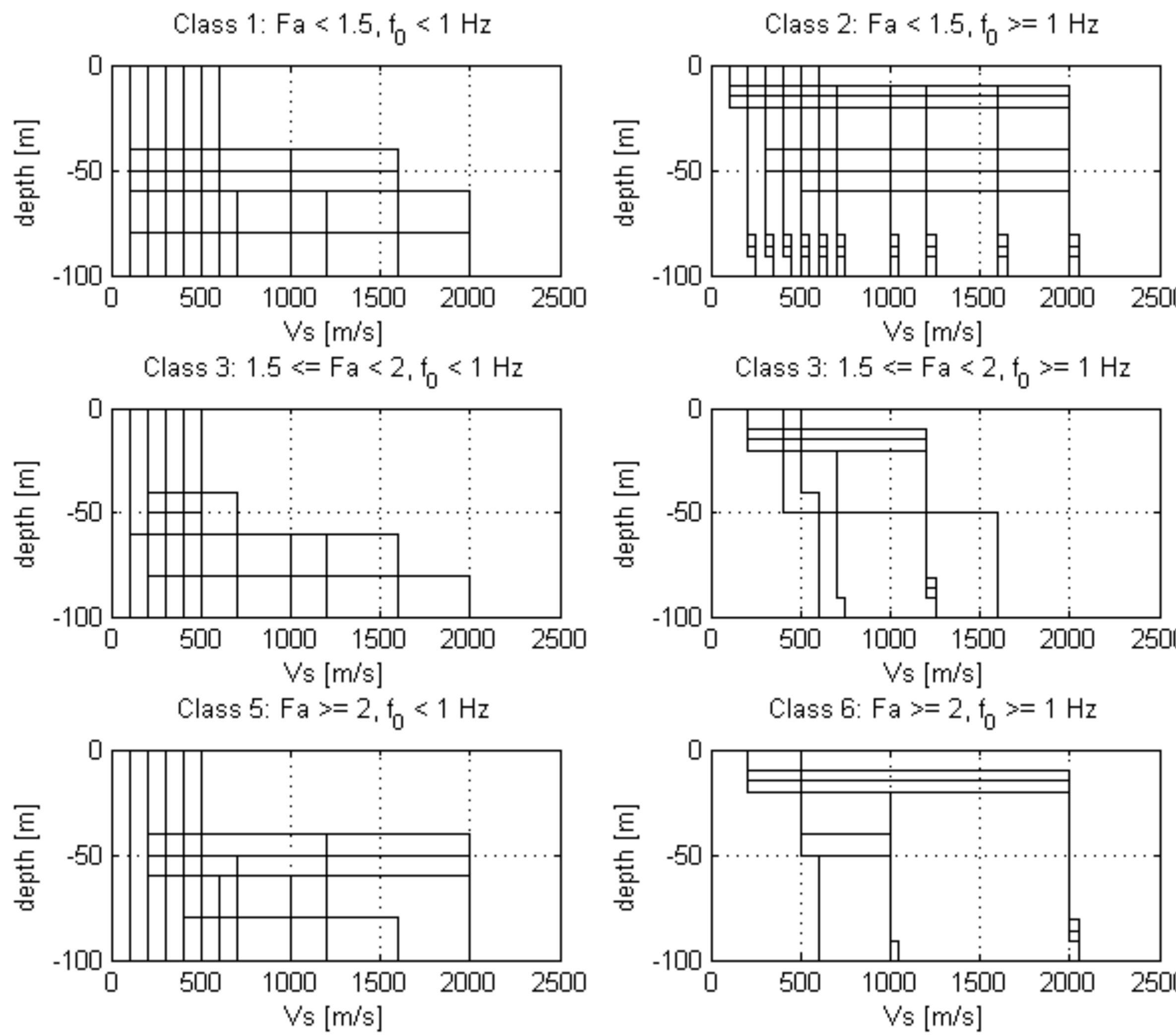
- We do not feel the need to fix any boundary between new site classes because this procedure – if rigidly instead of statistically interpreted – adds up problems at the class boundaries (Mulargia and Castellaro, SRL, 2009).
- However, just to discuss the benefits of a classification based on Vs_0, f_0 and Z, we group our 585 soil models as shown below

Fa	f_0 [Hz]	f_0 [Hz]
[1 1.5[	< 1 (C1)	≥ 1 (C2)
[1.5, 2]	< 1 (C3)	≥ 1 (C4)
> 2	< 1 (C5)	≥ 1 (C6)



THE VFZ MATIRX

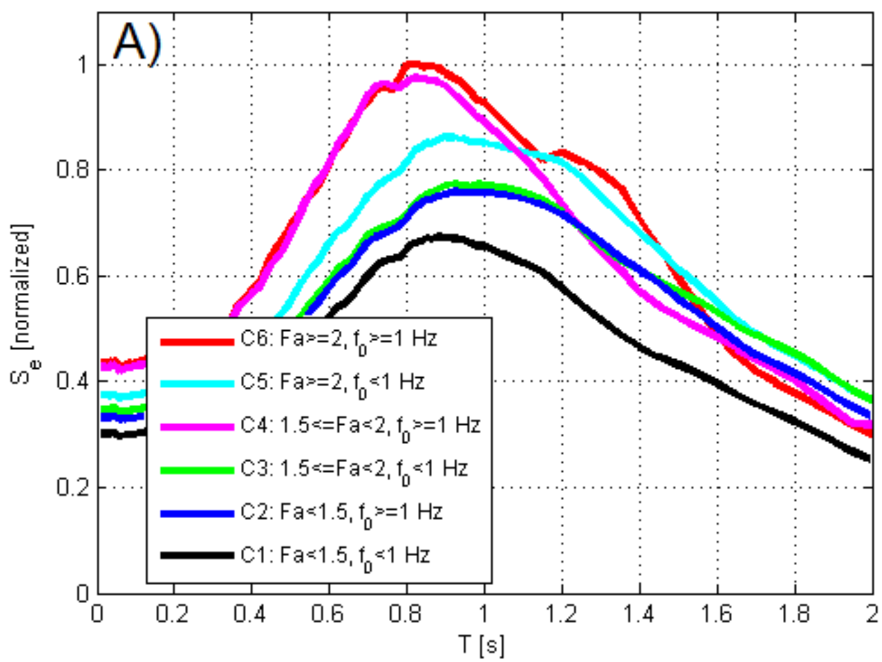
- As expected, $f_0 < 1$ Hz classes are related to subsoils with strong impedance contrasts at larger depths.
- However, several different models give the same amplification factors and a description of the different classes in terms of subsoil profile is not straightforward.
- This confirms the advantages of an alternative classification method, that does not take into account Vs-depth but the VFZ matrix.



THE VFZ MATIRX

Average response spectra derived from our models for each VFZ site class.

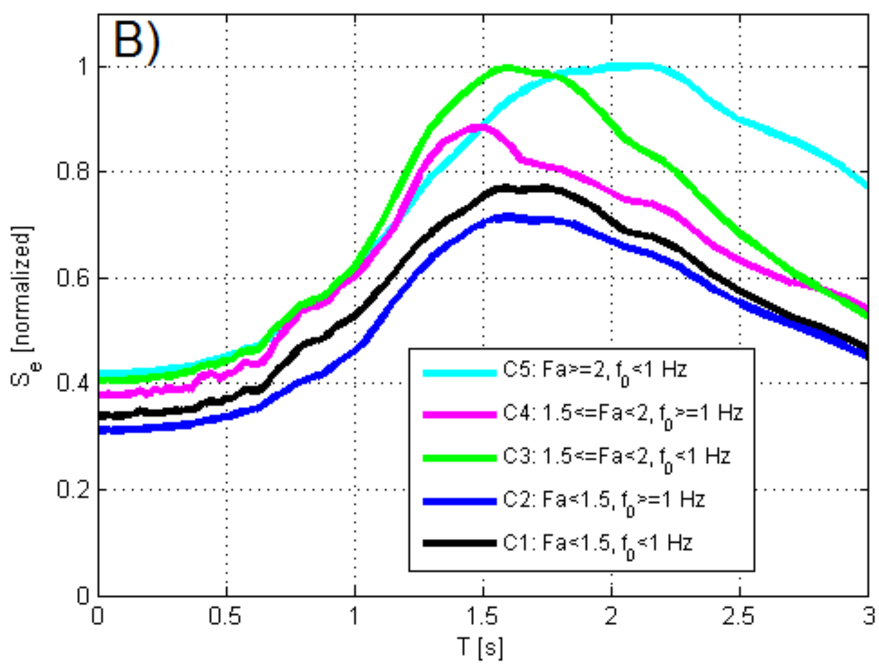
- Input: 1 Hz Ricker wavelet
  - The maximum acceleration in the response spectrum is expected on soils with Fa ≥ 1.5 and f_0 ≥ 1 Hz, which is intuitive.
  - The minimum acceleration is expected on soils with Fa < 1.5 and f_0 < 1 Hz.



THE VFZ MATIRX

Average response spectra derived from our models for each VFZ site class.

- Input: 0.5 Hz Ricker wavelet
  - The maximum acceleration is expected on soil classes with Fa ≥ 1.5 and f_0 < 1 Hz, which is again intuitive.
  - The minimum acceleration is expected on soils with Fa < 1.5 and f_0 ≥ 1 Hz.

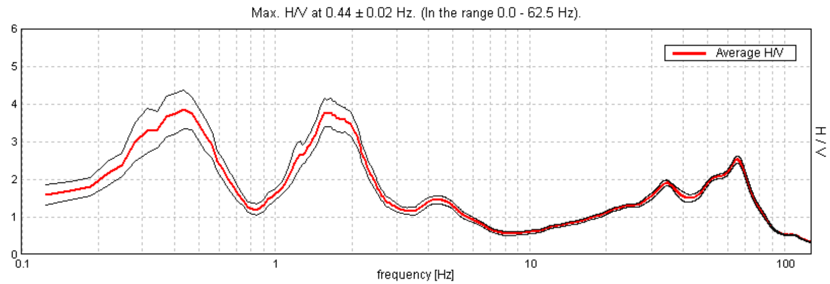


THE VFZ MATIRX IN PRACTICE

Vs_0, f_0, Z

- There exist a number of ways to measure or derive them from field surveys and we will not discuss all of them.
- However, it has to be noted that Vs_0, f_0 and Z have to be determined in the whole range of engineering interest ~[0.1-20]Hz, which corresponds approximately to 1 km to 1 m depth.

HOW TO EXPLOIT THE MICROTREMOR H/V FOR THE VFZ SITE CLASSIFICATION METHOD



It is probably the easiest method to:

1: provide an acceptable estimate of f_0 in the whole engineering range of interest [0.1-20] Hz (SESAME, 2005)

2: identify impedance contrasts Z

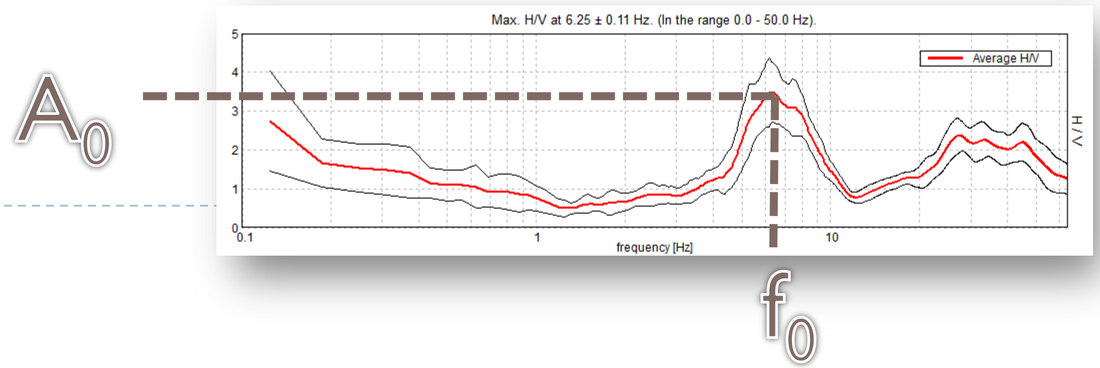
THE VFZ MATIRX IN PRACTICE

Vs_0, f_0, Z

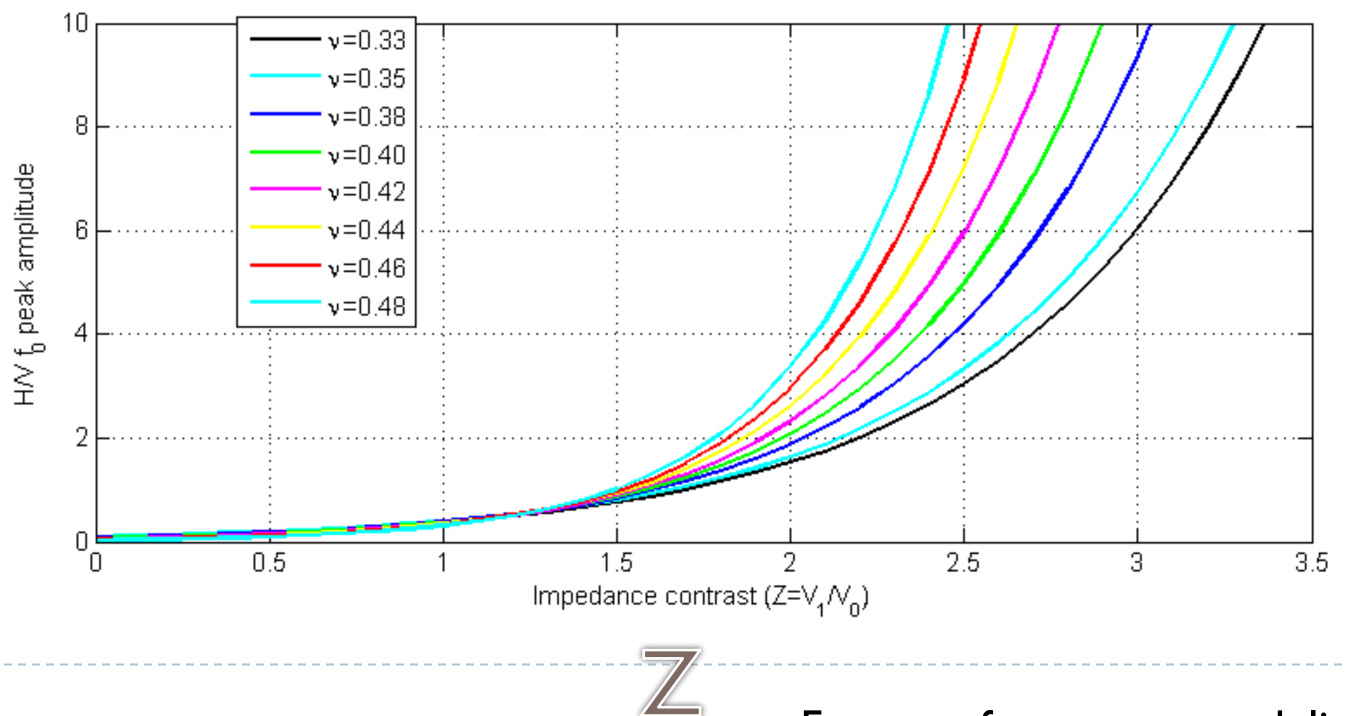
- We will focus on how to use the microtremor H/V method (even though not used alone) to come to a VFZ classification.

It is widely accepted that microtremors are essentially surface waves, therefore the H/V peak amplitude is *not* linearly related to the SH-transfer function.

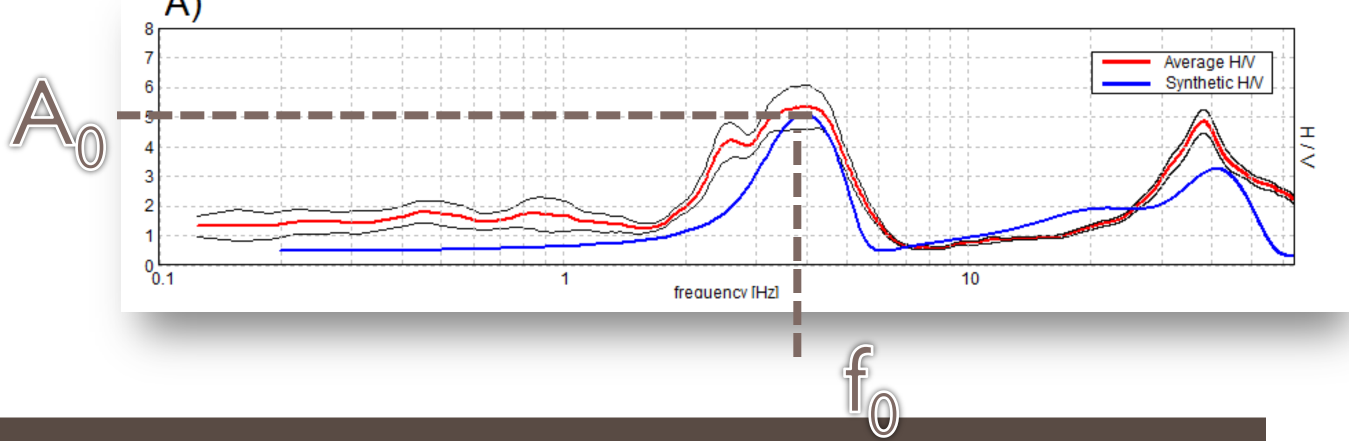
However, there exists a general relation between the H/V peak amplitude and the impedance contrast that generates it.



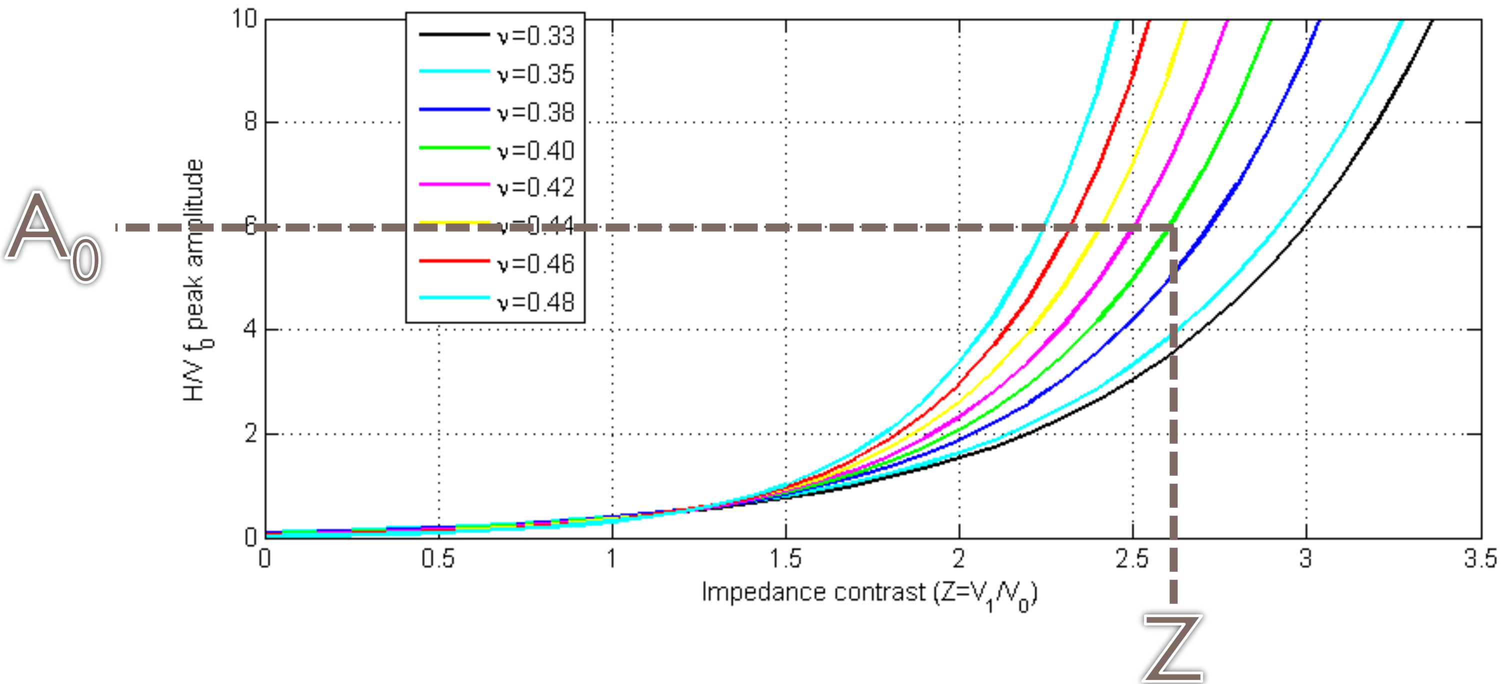
General relation between the H/V peak amplitude and the impedance contrast that generates it



From surface waves modeling

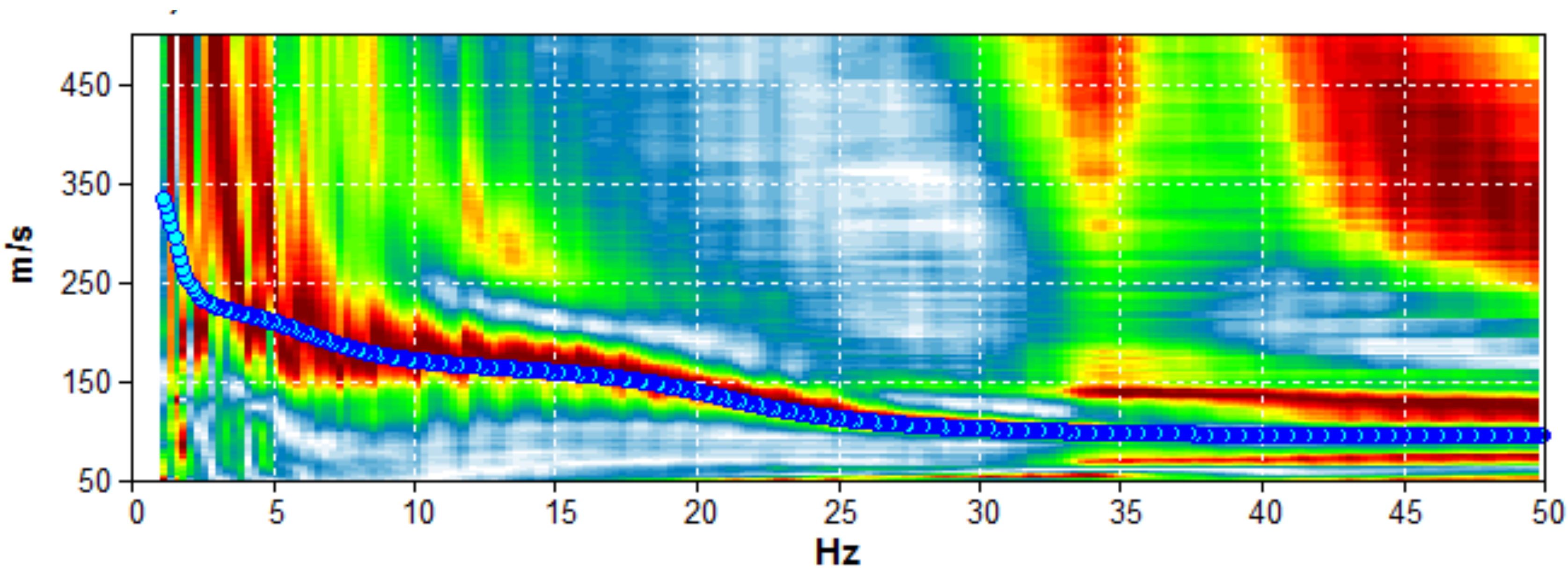


We get the impedance contrast Z from A_0



Vs0

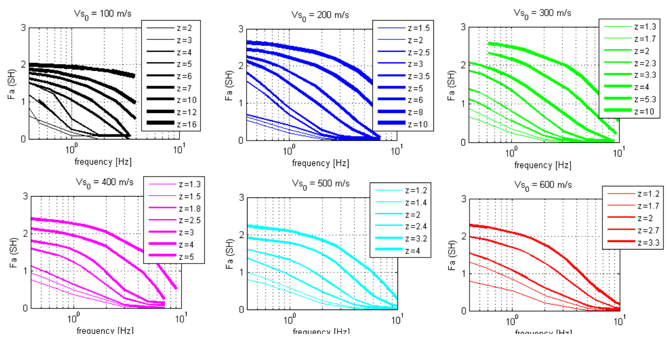
can be provided by any array or similar technique

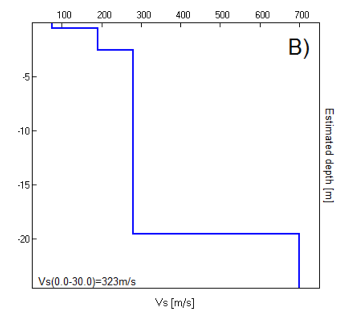


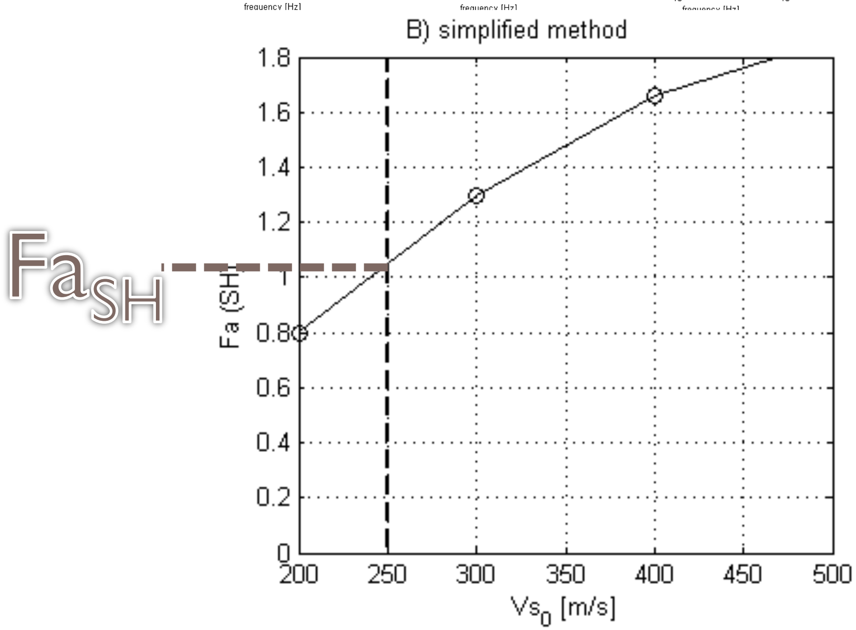
Now we have all the information to enter the VFZ matrix and get a first-order approximation of the SH amplification ratio at f_0

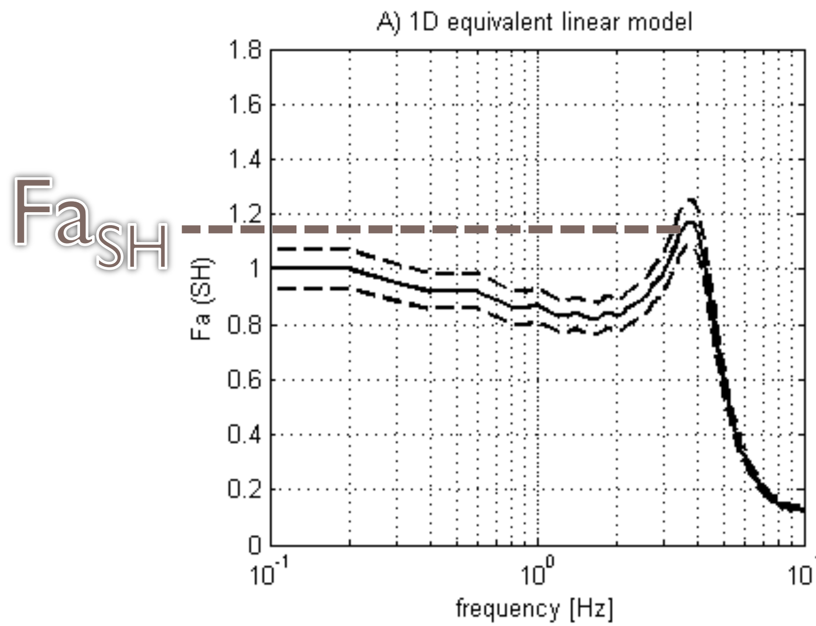
VFZ matrix method

1D numerical modeling







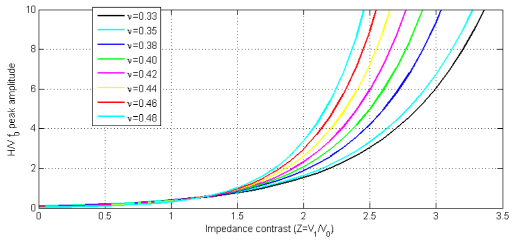


THE VFZ MATRIX IN PRACTICE (2)

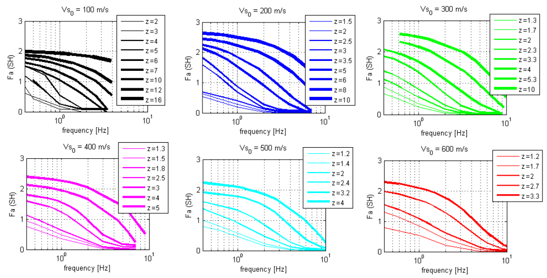
We have seen the case of a subsoil with a single impedance contrast

HOW TO DEAL THE CASE OF NO SPECIFIC RESONANCES ON SOFT SOILS (slowly increasing Vs)?

Z <1.5 do not give significant H/V peaks.

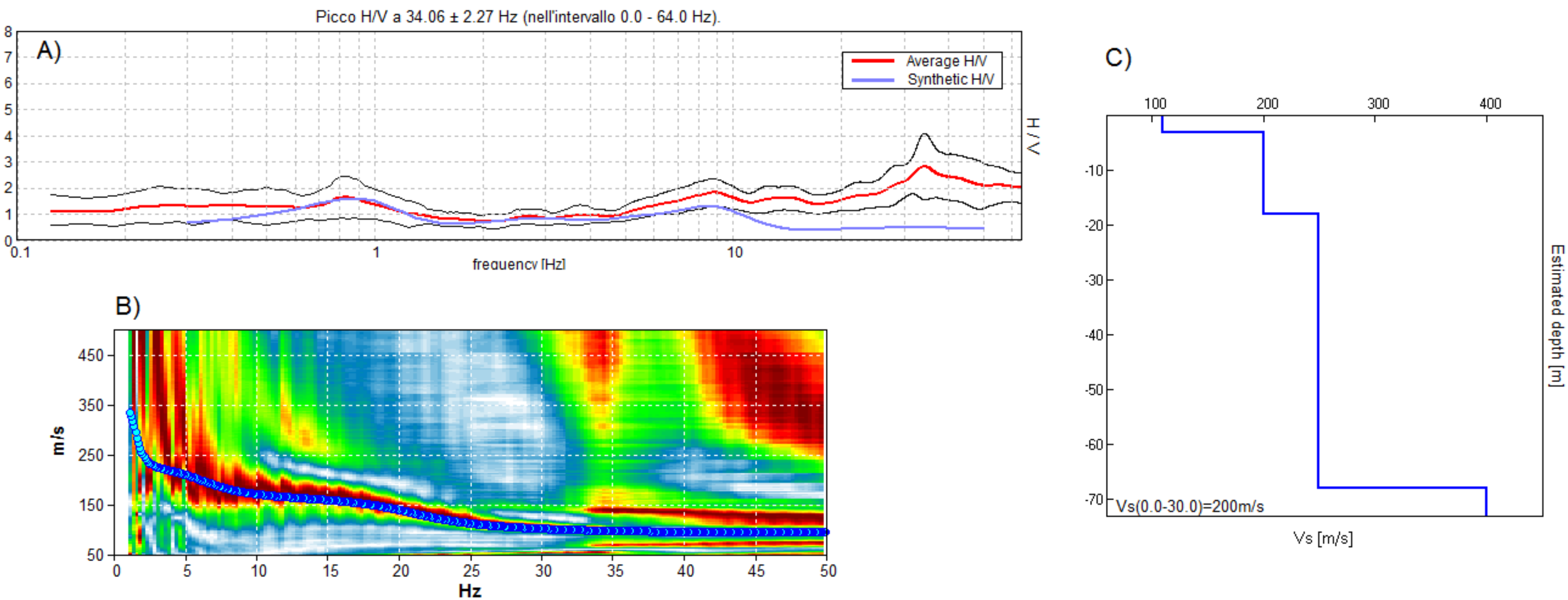


In the same way, significant amplification ratios are expected for SH waves only for Z > 2.



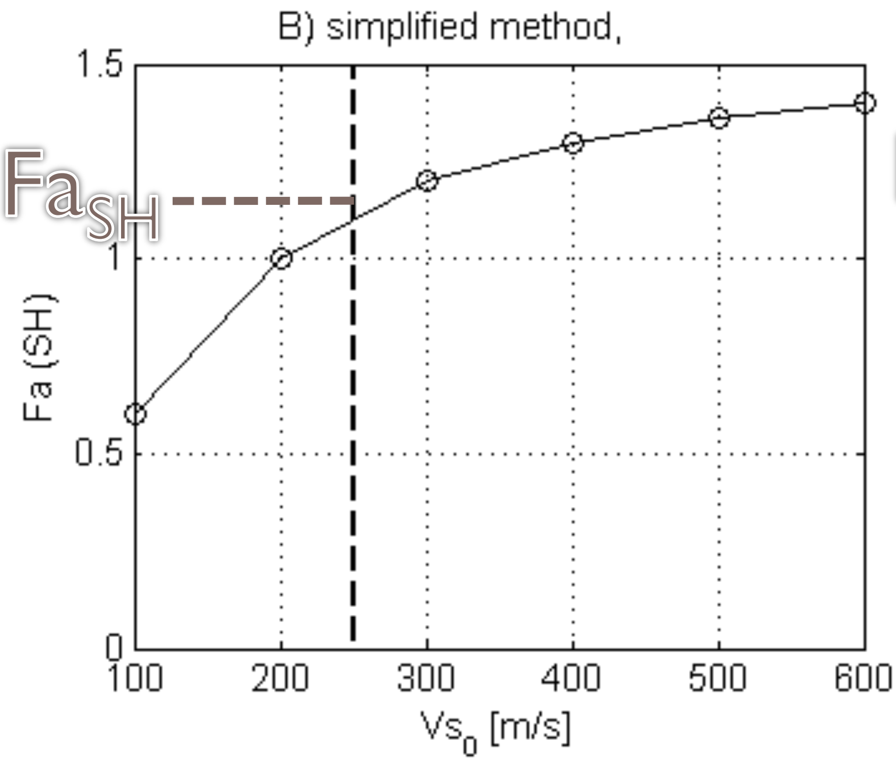
THE CASE OF WEAK IMPEDANCE CONTRASTS

As a consequence, when no clear H/V peaks can be recognized in the H/V curve, this stands for a low Z and the resulting SH amplification factor can be estimated by following the low impedance contrast lines for the specific Vs_0.

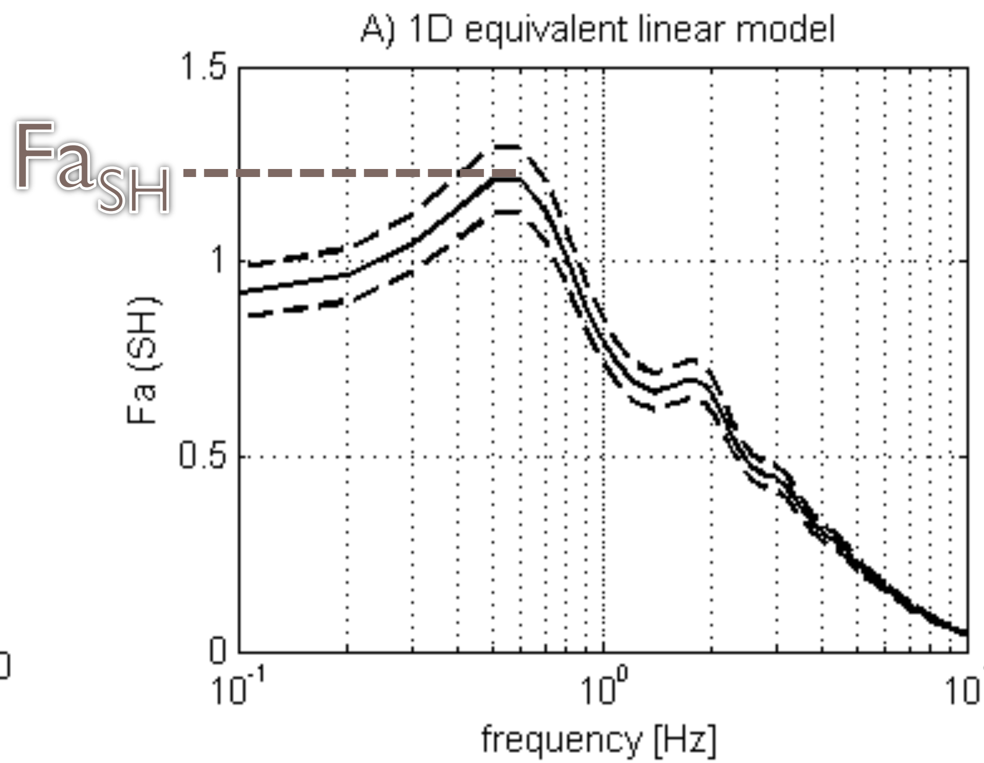


THE CASE OF WEAK IMPEDANCE CONTRASTS

VFZ matrix method

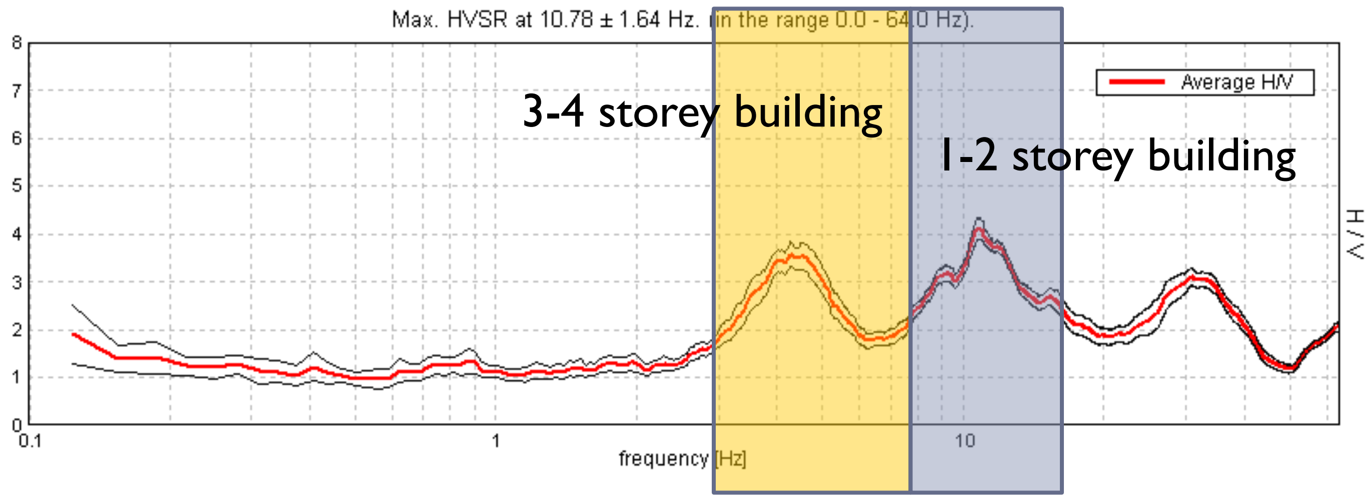


1D numerical modeling



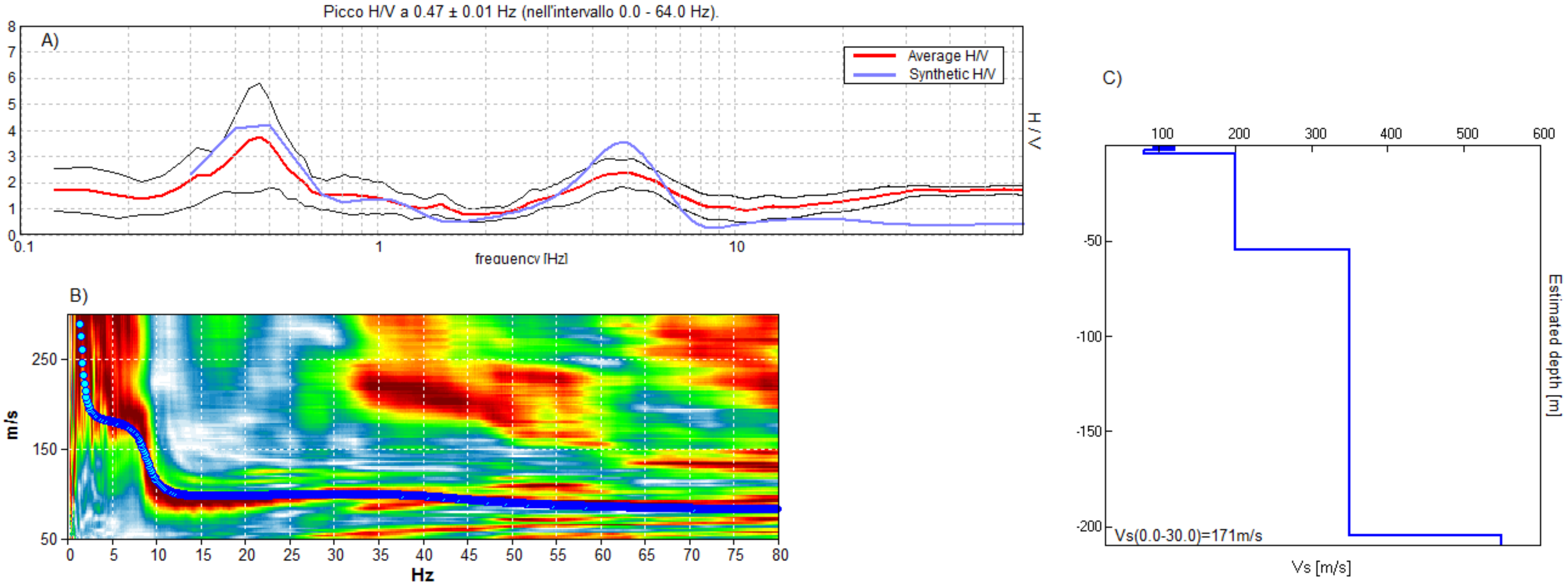
THE VFZ MATIRX IN PRACTICE

HOW TO DEAL THE CASE OF SEVERAL IMPEDANCE CONTRASTS?



The simplified approach will be applied to the H/V peak closer (in terms of frequency) to the fundamental mode of the building for which we are evaluating the soil response.

THE CASE OF SEVERAL IMPEDANCE CONTRAST

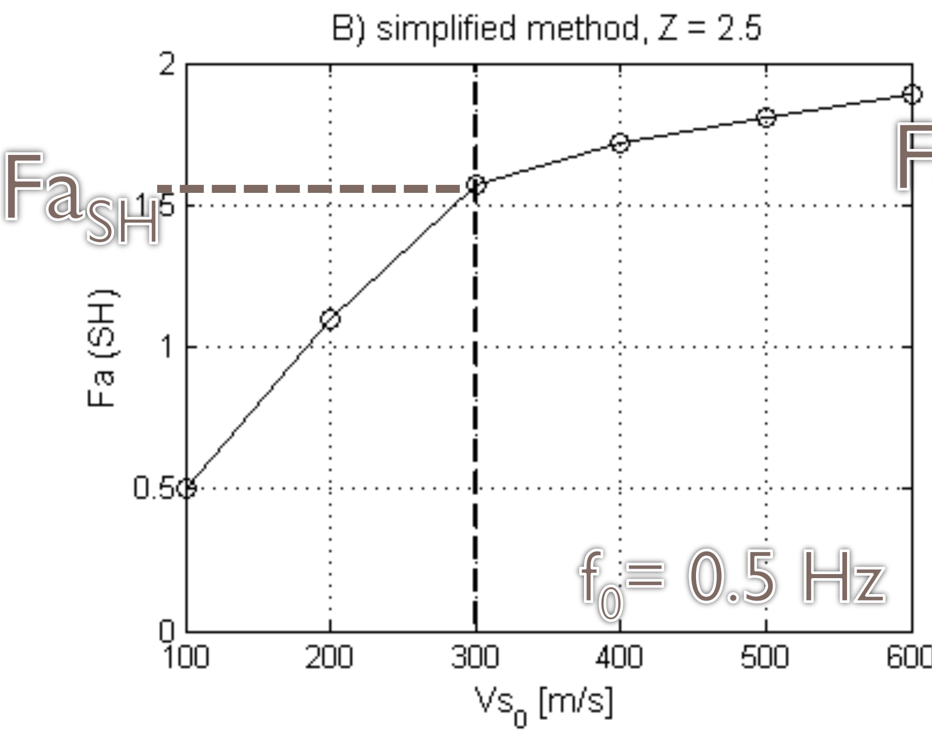


In no way is the H/V peak at 5 Hz a higher mode of the 0.5 Hz peak.

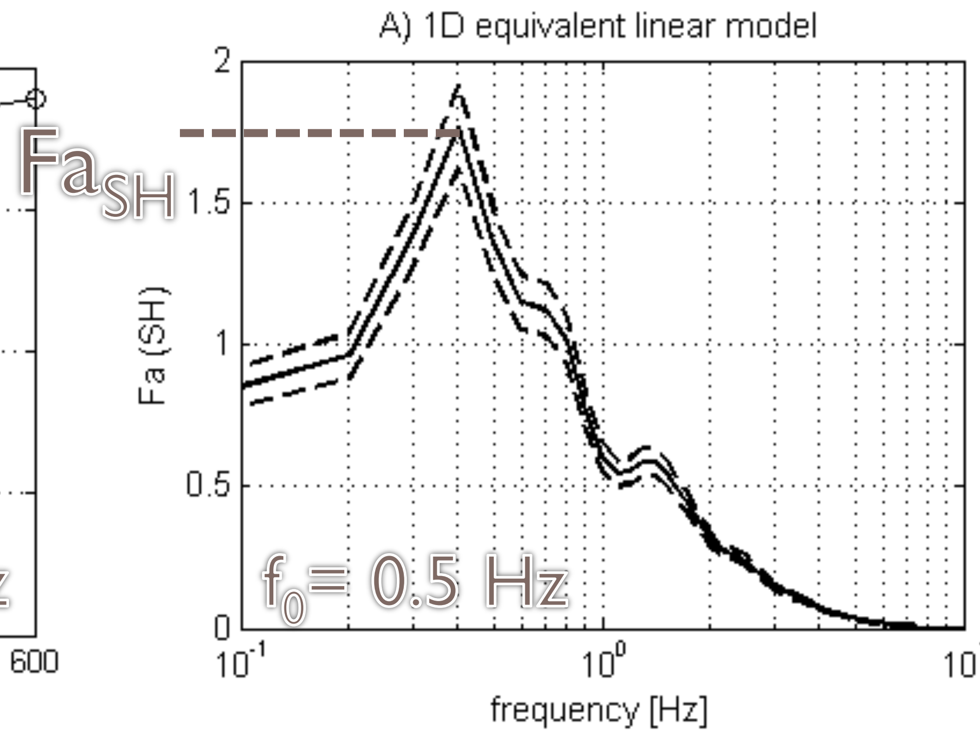
The first is related to a overconsolidated clay layer at about 10 m depth while the low-frequency peak is to be related to the local bedrock located at about 200 m depth.

THE CASE OF SEVERAL IMPEDANCE CONTRAST

VFZ matrix method



1D numerical modeling



By using the simplified approach, if we consider as the relevant frequency 5 Hz, then we have Vs_0 = 100 m/s, Z = 2 and Fa is negligible

CONCLUSIONS (1/3)

- The final goal of site effect assessment is to predict the behavior of an oscillator (the structure) founded on another oscillator (the subsoil).

  We therefore propose to shift the reasoning from a depth-dependent approach (Vs30) to a frequency dependent approach (f_0).

- By observing that the main cause for stratigraphic seismic amplification is the existence of impedance contrasts in the subsoil, we propose a simplified seismic site classification scheme (the VFZ matrix) based on: Vs_0, f_0 and Z, which are measurable in the whole range of engineering interest (0.1-20 Hz).

CONCLUSIONS (2/3)

- In the VFZ matrix approach we do not need to set threshold values to characterize what a bedrock is.

- By numerically studying the 1D soil response on different soil models (all characterized by Vs increasing with depth), we create the 4D function that relates the expected SH-wave amplification factor Fa to (Vs_0, f_0, Z).

- Several methods exist to estimate (Vs_0, f_0, Z), however the microtremor H/V technique is here preferred to assess (f_0, Z) because there are no techniques as easy as H/V to get a first order idea of the soil stiffness trends in the subsoil in the whole frequency domain of interest.

CONCLUSIONS (3/3)

- The H/V is also capable to suggest the presence of relevant velocity inversions (Castellaro and Mulargia, PAGEOPH 2009), that is cases which have not been considered in our models yet.

- The proposed classification scheme based on the VFZ matrix can be used also on sites where no specific resonances are measured (due to the absence of sharp impedance contrasts) and on soils presenting several resonances.

In this meeting I've seen a similar approach presented in a poster by Cadet, Cultrera, De Rubeis and Bard, where they propose:

→ f_0

→ the Rayleigh wave dispersion curve (Vs_0 down to at least 3.3 f_0)

as proxies to Fa_{SH}.

They derived their approach from experimental observations (they used Japanese earthquake data).

We derive our approach from numerical models and we add Z, which releases the need to define what a bedrock is, but essentially we are going towards the same direction.

This is not refined Physics*,
but at least is a physical approach to the Fa_{SH} estimation problem.

* and we don't want it to be because it is a simplified approach for the daily practice!