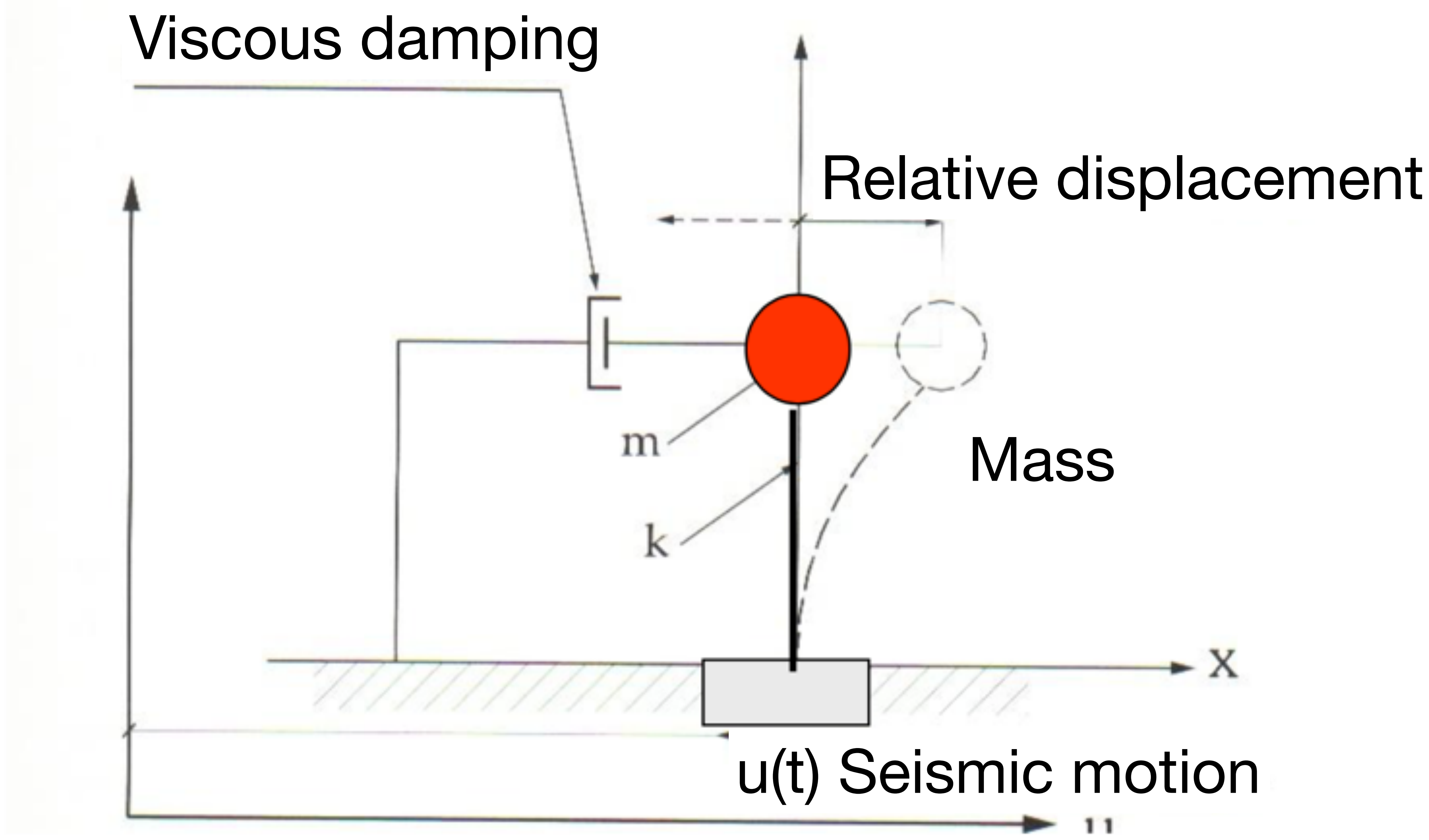
The Response Spectra

The Response Spectra
Seismic Action

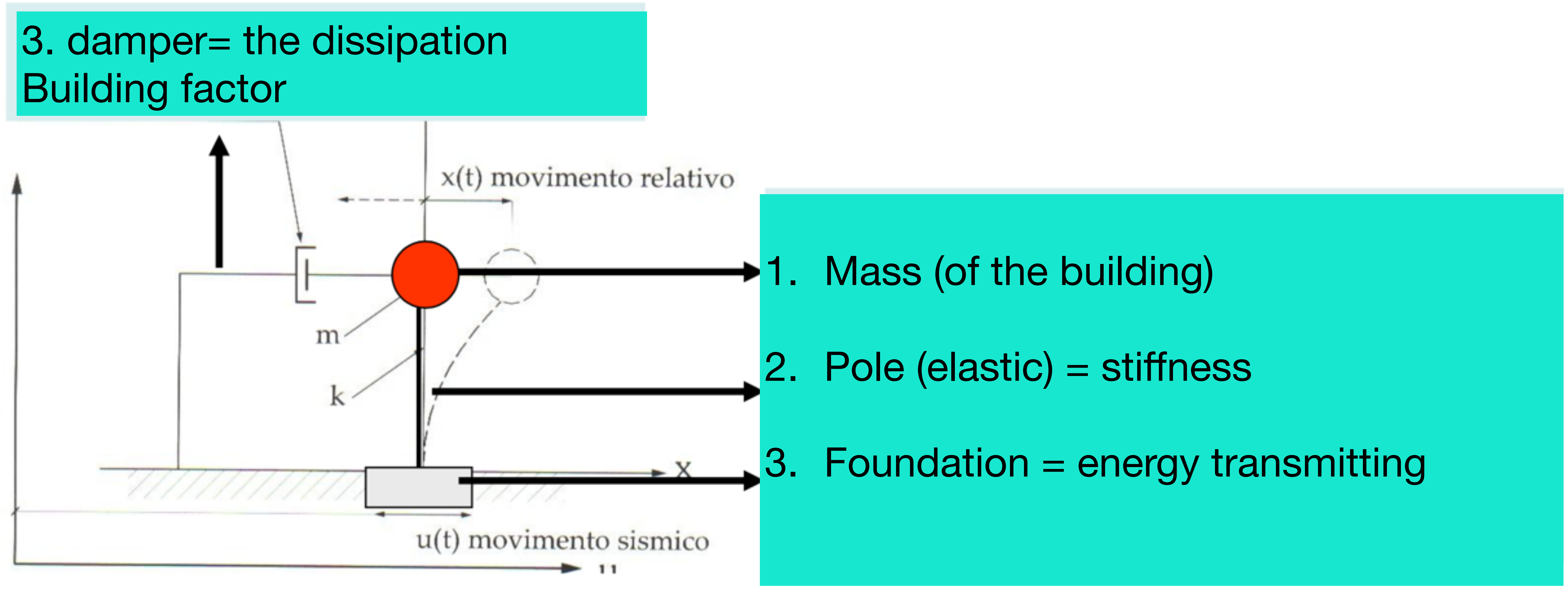
The final displacement is an **oscillatory motion**

The simplified assumption for building shaking under seismic action is the **Simple pendulum**



Simple Pendulum

Simple pendulum it is possible to identify the building factors response

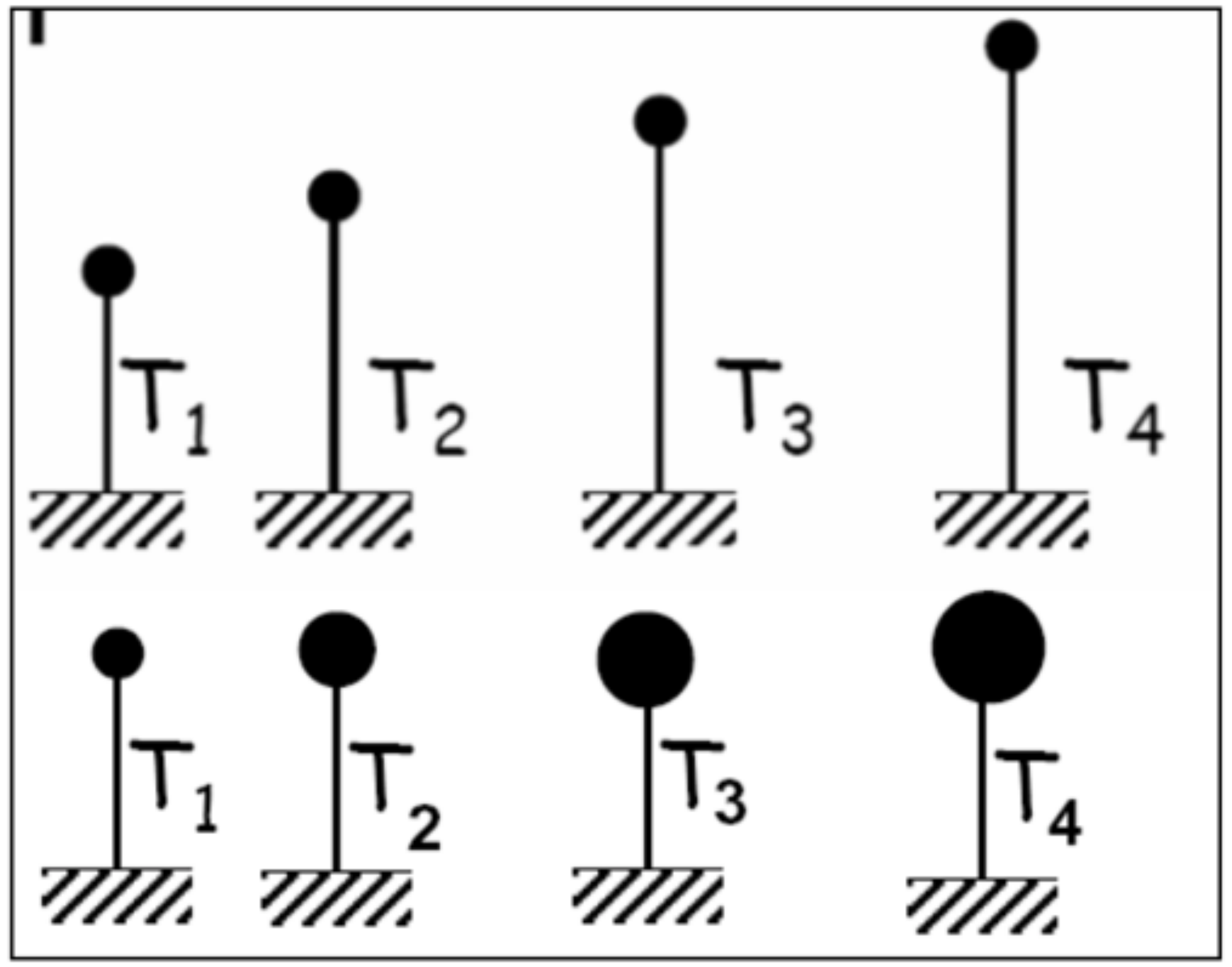


Simple Pendulum Period

Simple pendulum period is function of mass **m** and stiffness **k**

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{m}{k}} \quad \text{[sec]}$$

Varying Period T



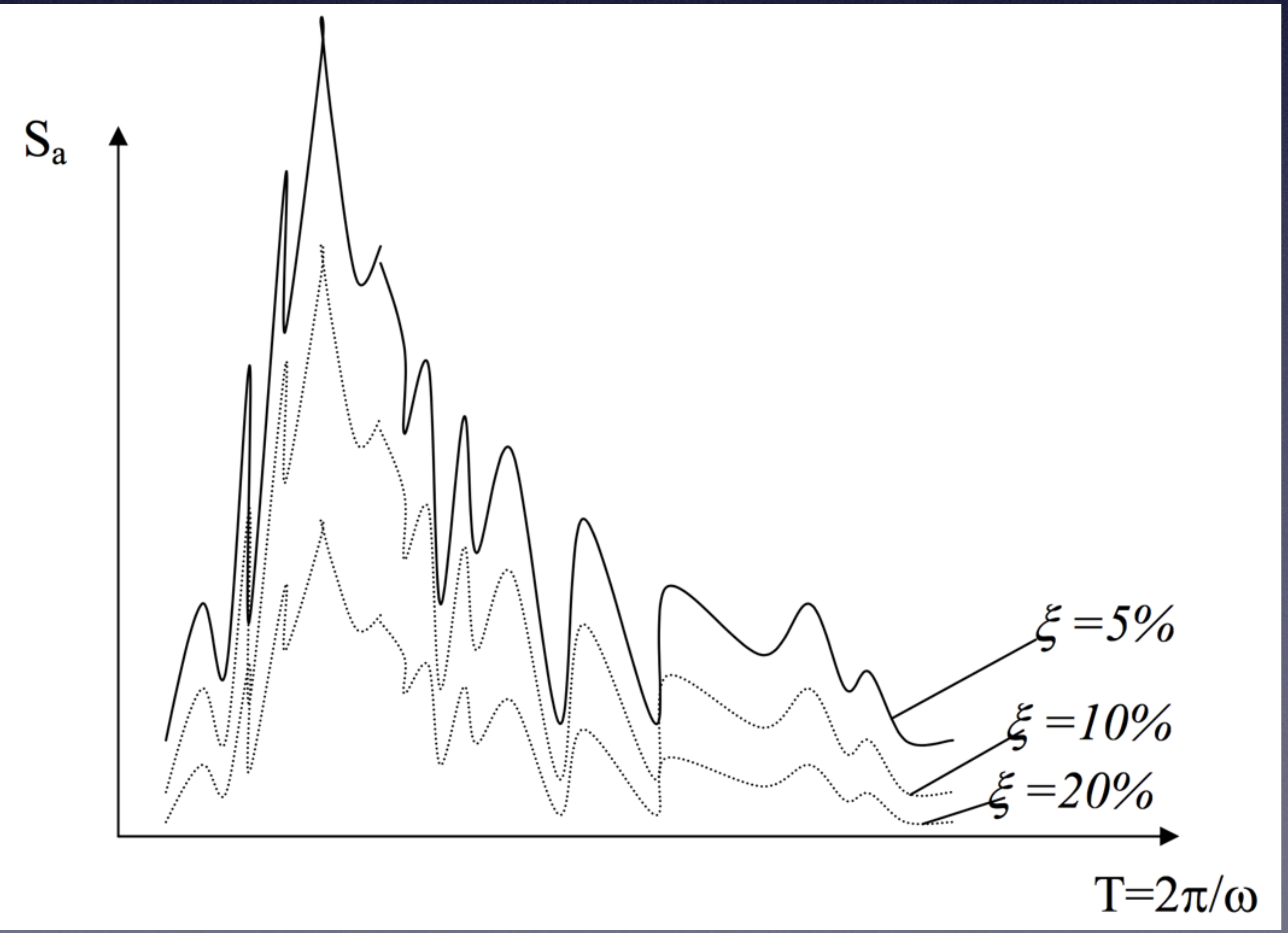
M cost , k decrease

K cost, m increase

The Response Spectra

The response spectrum represents the maximum response in acceleration (velocity or displacement) of all the possible simple pendulum, with the same damping, given the same input.

It plots in y axis the values of pseudoacceleration, S_a, or pseudovelocity SV, or maximum dispacement SD, obtained varying stiffness k (and then the period T in the x axis) , given a fixed damping ξ.



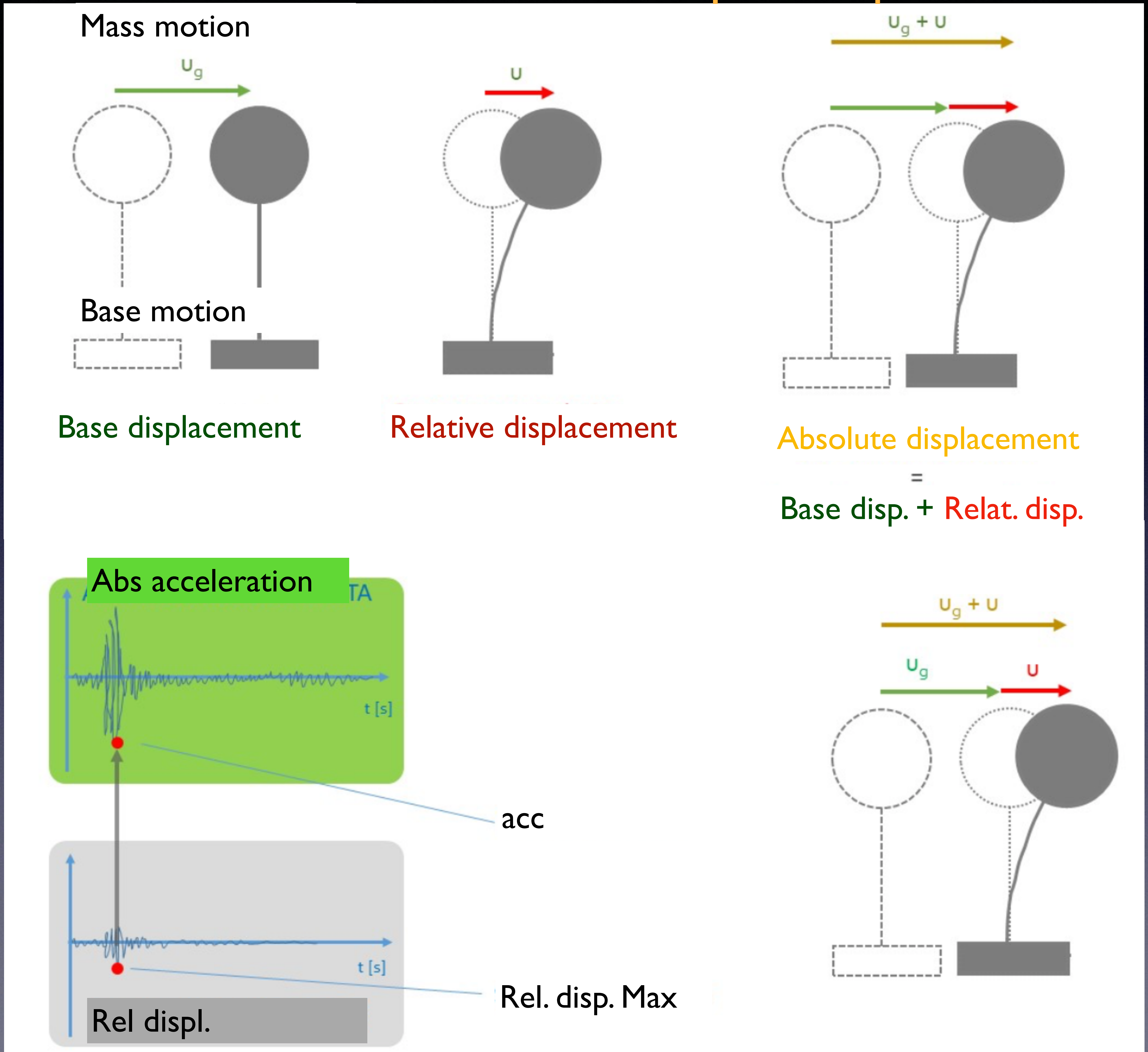
Why Pseudo?

Cause Max acceleration may not be

Related to the maximum displacement…

The Response Spectra

Cause the base is not fixed…



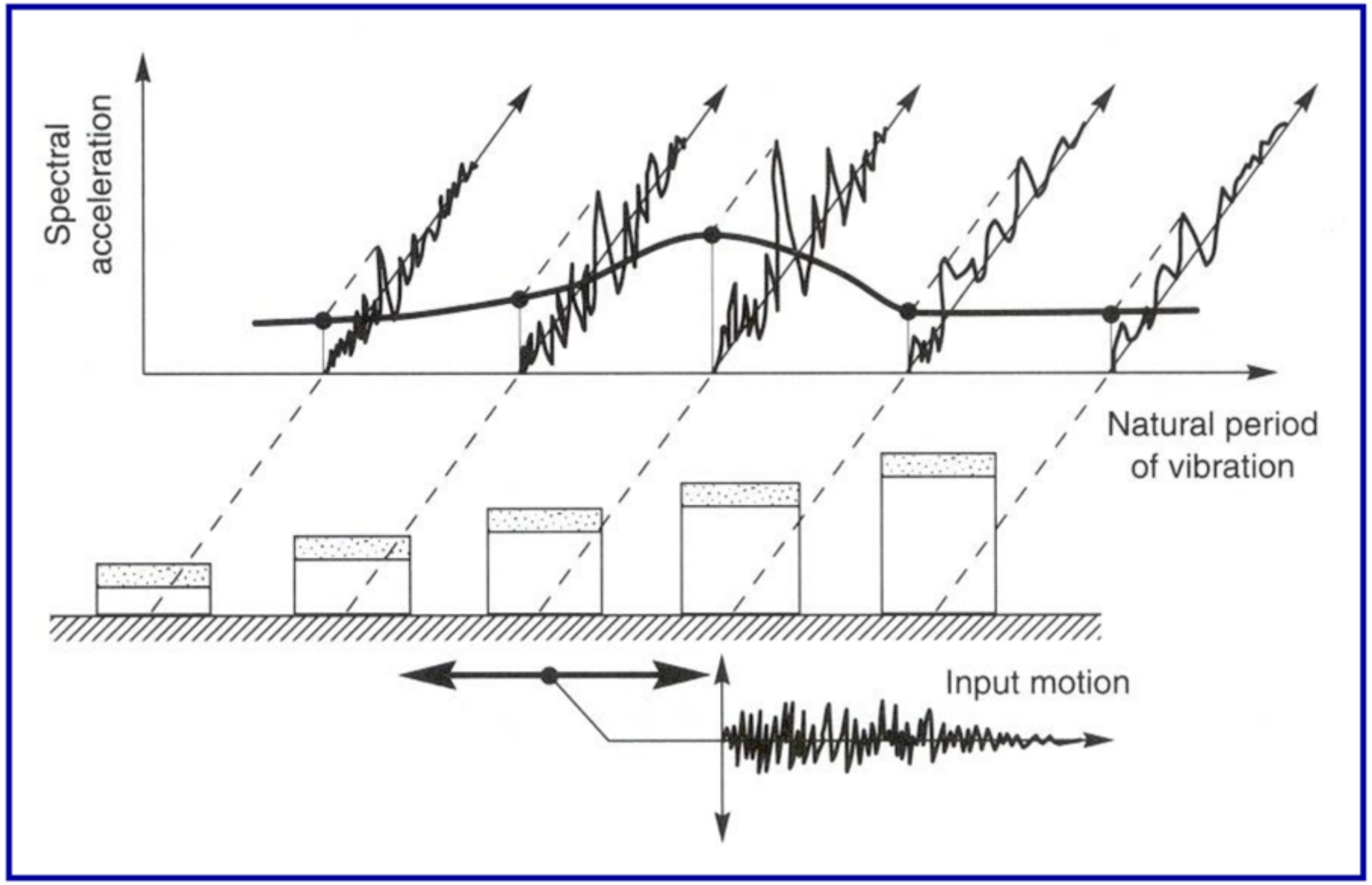
- We want the Maximum solicitation
- the max solicitation is when the **relative** displacement is maximum
- the acceleration at the moment of maximum displacement cannot correspond to the absolute maximum
- this is why we call it Pseudo-acceleration

The Response Spectra

Fain

Fundamental Period of pendulum

The fundamental period (function of Mass and stiffness)
rules the seismic action response

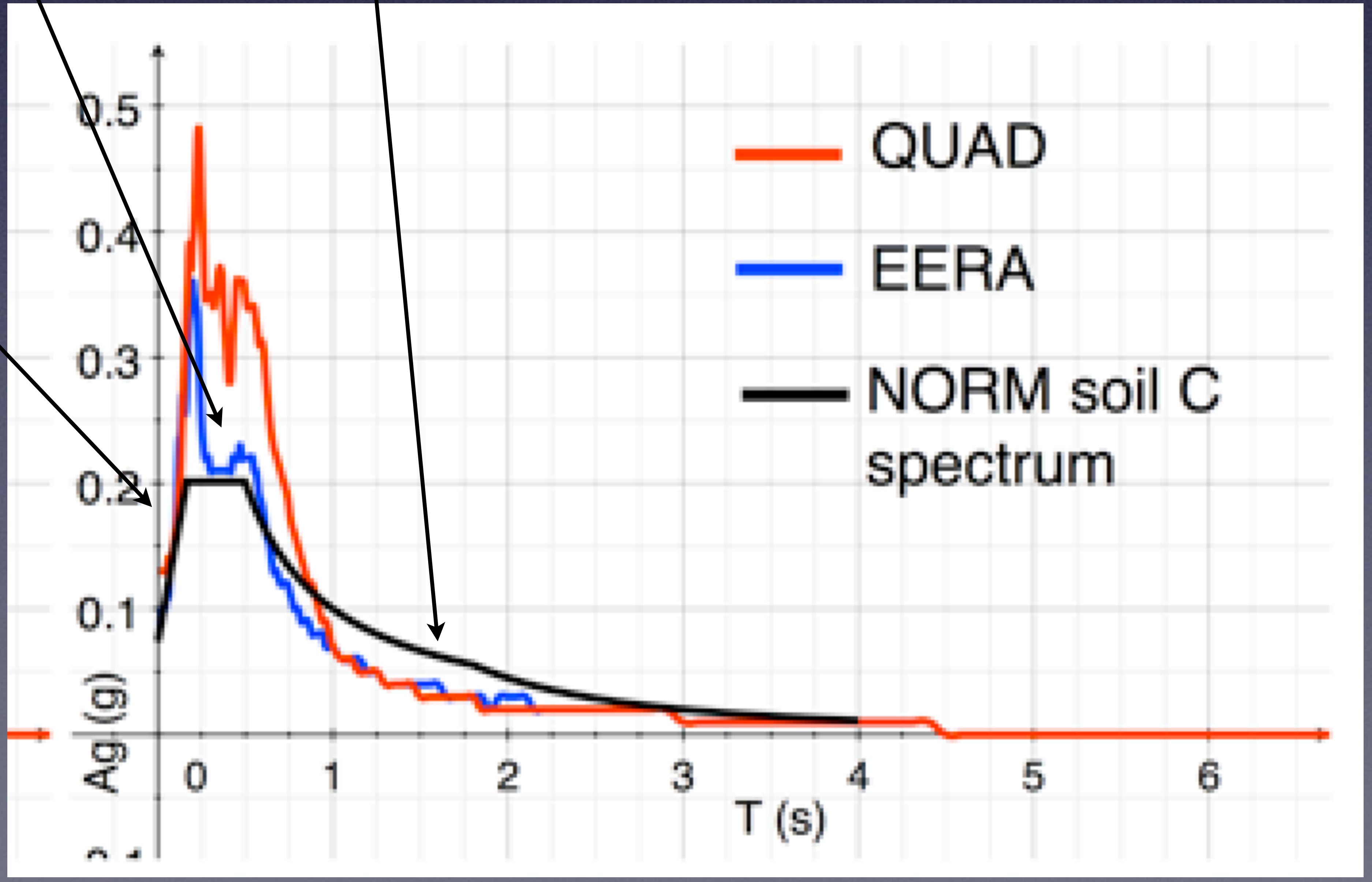


Frequency of Building Vibration

Buildings of different heights sway at different frequencies, like inverted pendulums, as shown in the following figure.

SHORT BUILDING	MID-HEIGHT BUILDING	TALL BUILDING
• Rigid 1- to 2-story building oscillates at 5–10 Hz.* • Shakes back and forth rapidly (high frequency). • Thus, period is 1/5 to 1/10 = 0.2–0.1 sec.	• 5- to 10-story building oscillates at 0.5–3.0 Hz. • Shakes back and forth less rapidly (intermediate frequency). • Thus, period is 1/0.5 to 1/3 = 2.0–0.3 sec.	• Flexible 20-story building oscillates at ~0.2 Hz. • Sways back and forth slowly (low frequency). • Thus, period is 1/0 or 5 sec.

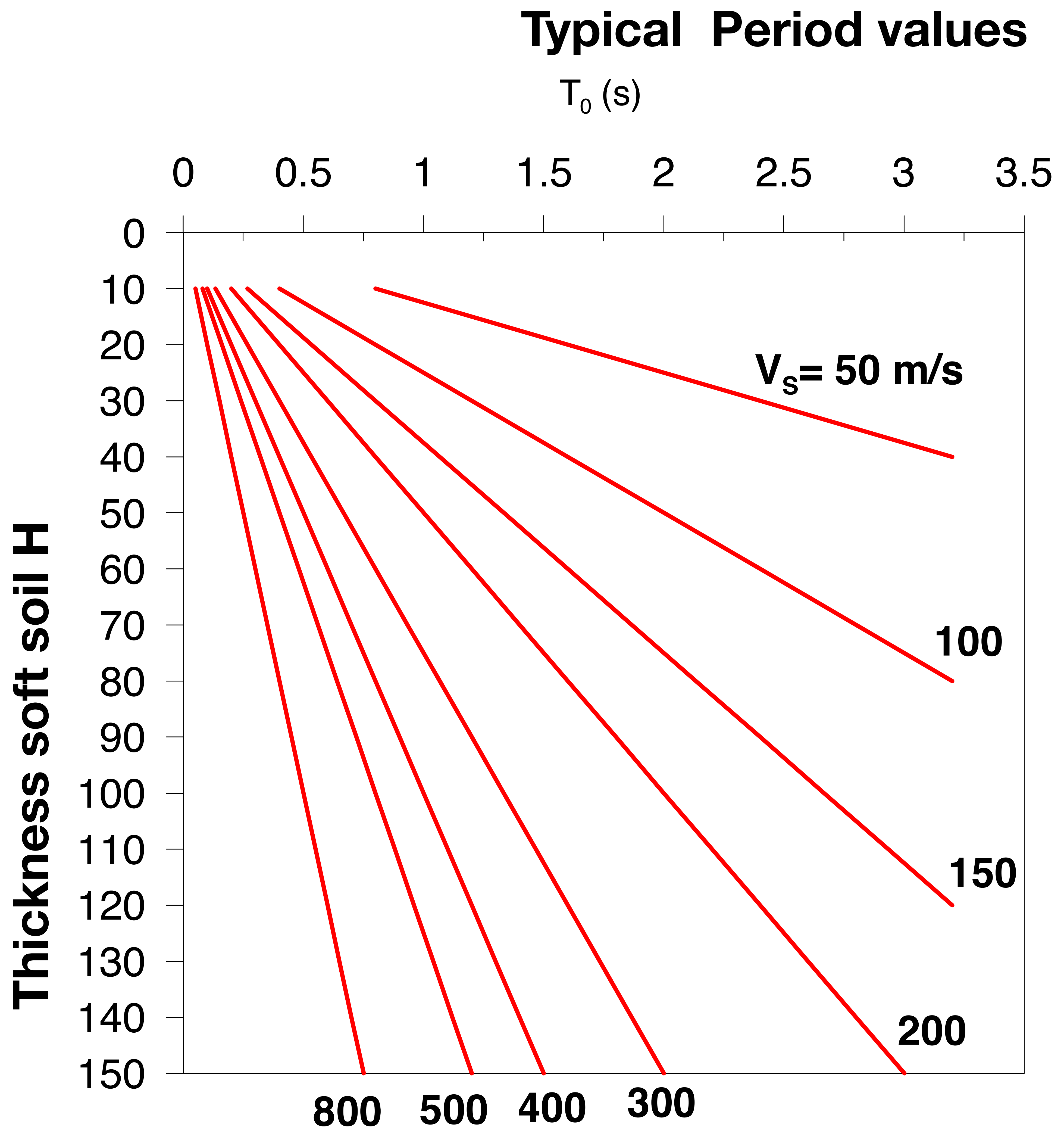
Hz = Hertz = cycles of back-and-forth motion per second.



Examples of
seismic response spectra

Resonance
Period
of soils
Is function of
Rigidity (Vs)
And thickness
of layer H

Seismic Response



$$T_0 = \frac{4H}{V_s}$$

$$f_0 = \frac{V_s}{4H}$$

Seismic Response

May we have resonance effect?

Typical soil fundamental frequency range:

$$f_0 = 0.25 - 10Hz$$

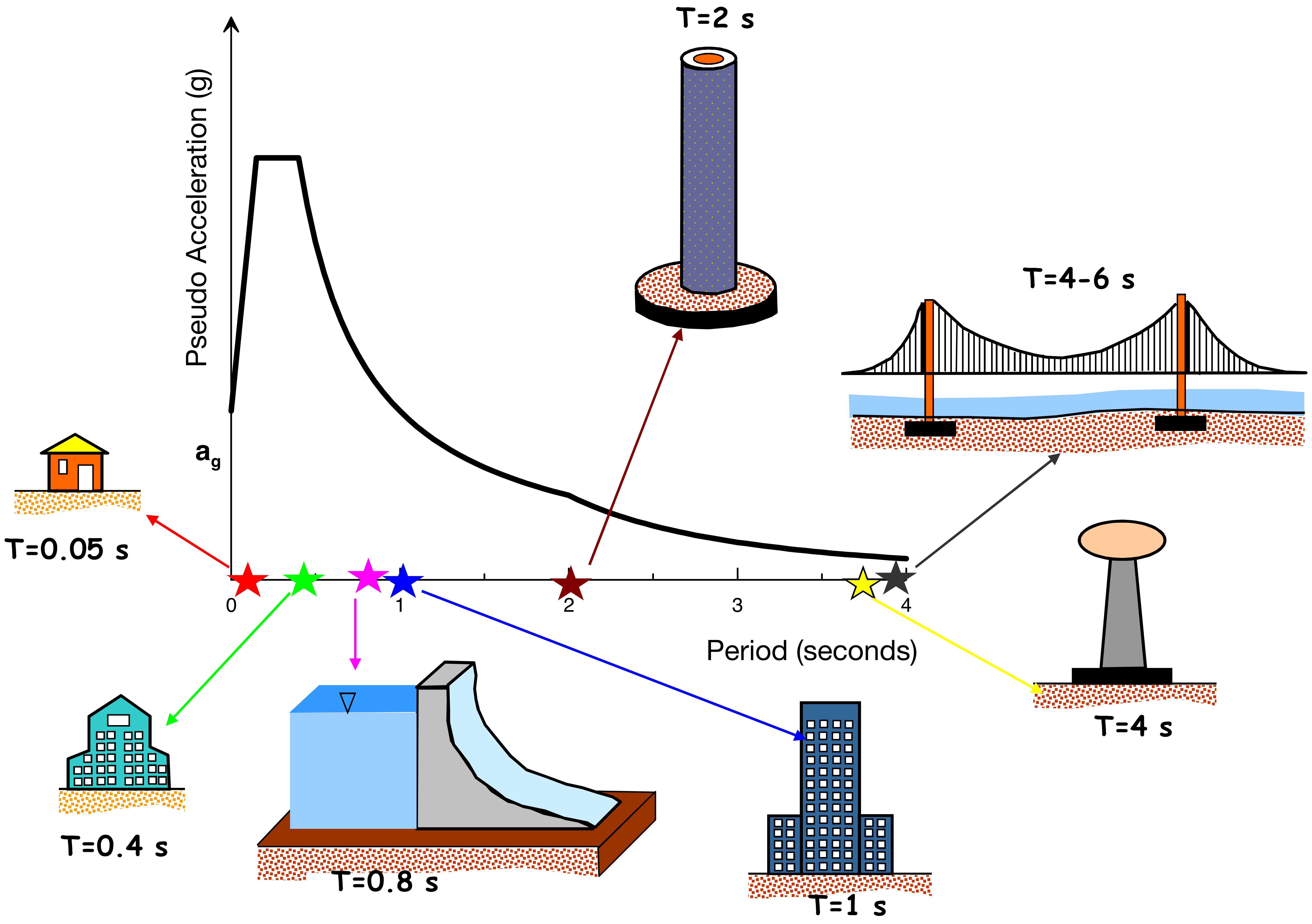
Typical earthquake range:

$$f_p = 0.1 - 20Hz$$

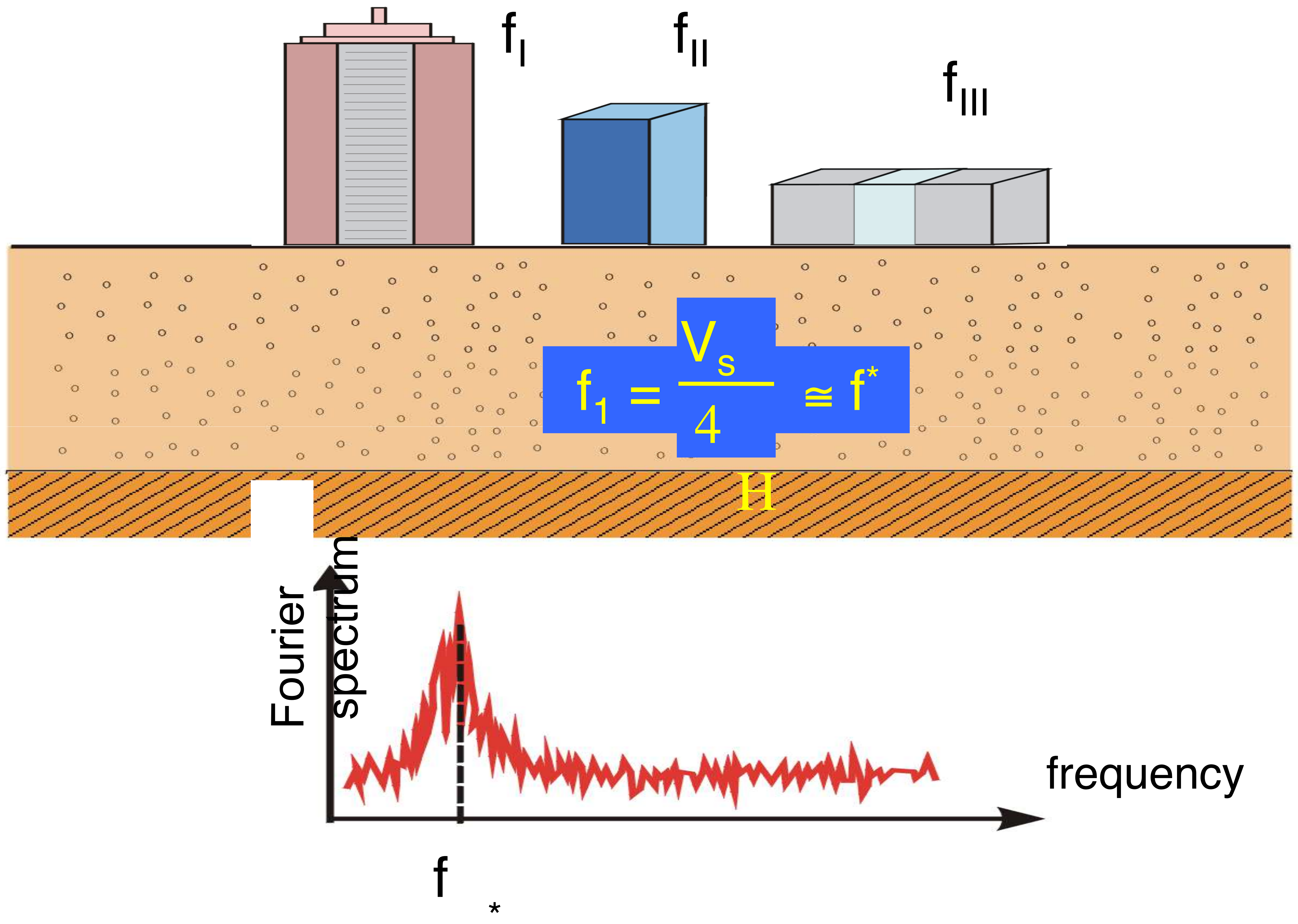
YES !!

Seismic Response

Period of typical building



Double resonance effect



Seismic Response

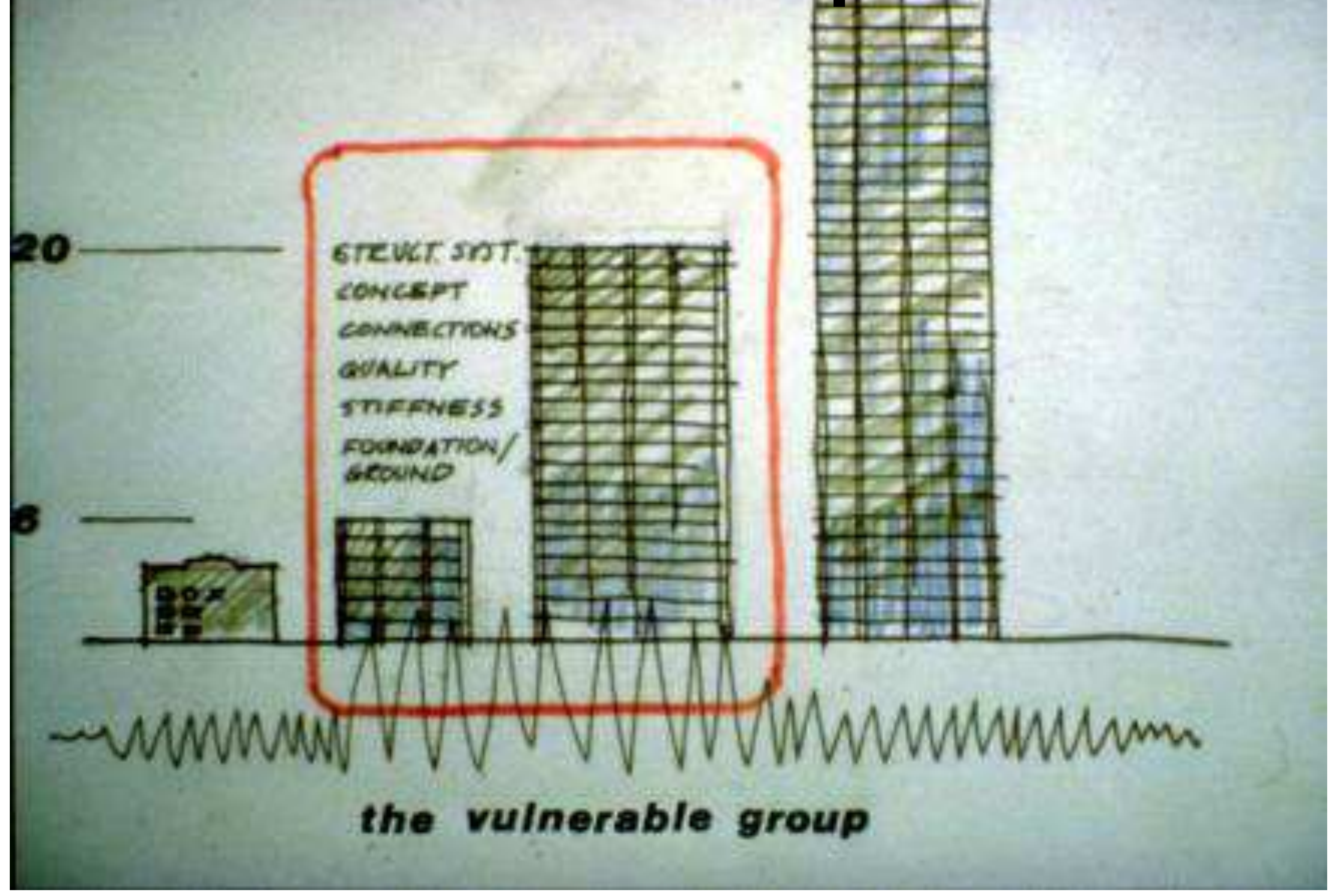
Mexico City 1986

Edificio di 21 piani in struttura metallica

Bilancio:
- 9000 vittime
- 5000 edifici danneggiati
- 500 edifici crollati

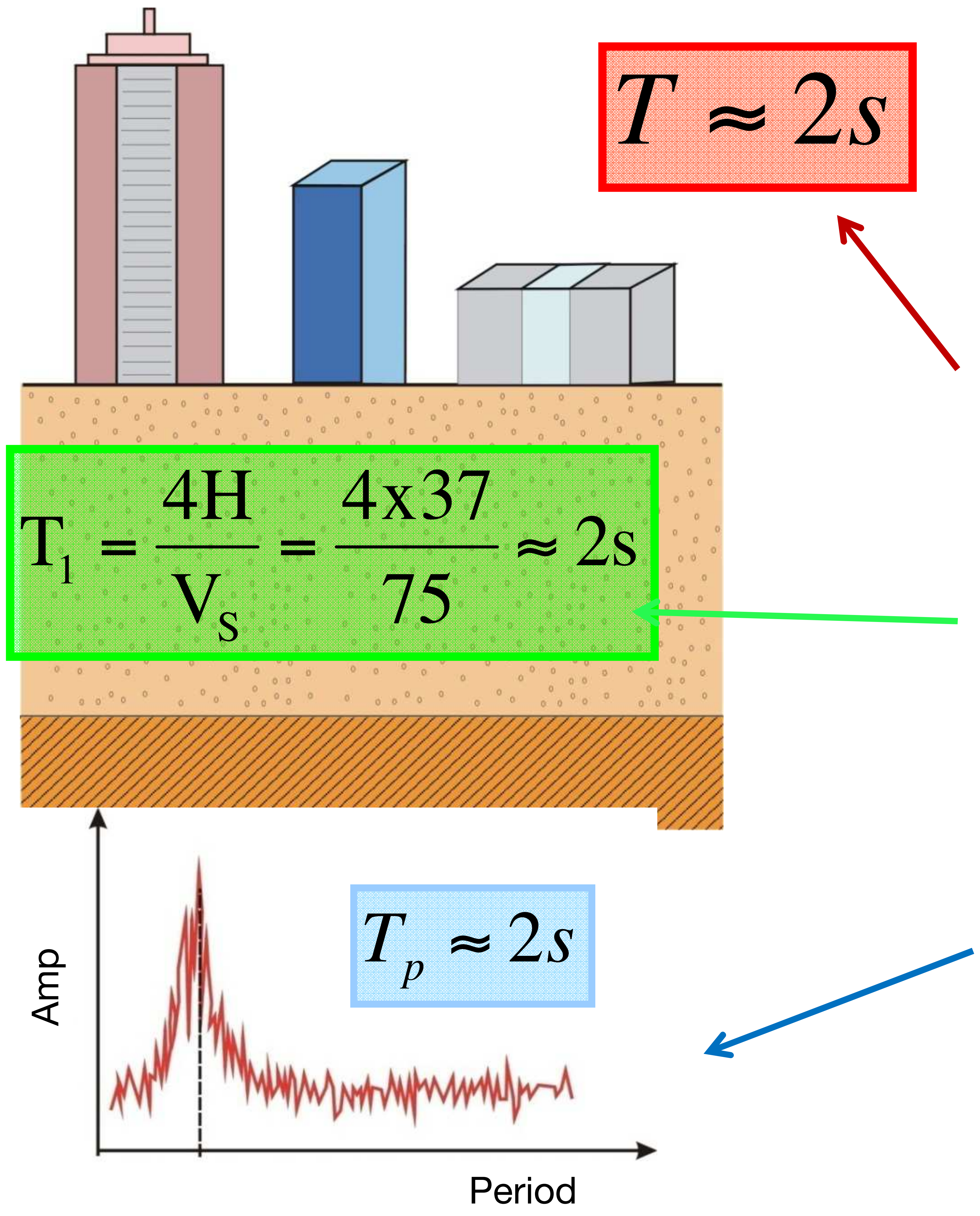
Come si giustifica la particolare distribuzione dei danni osservati tra le diverse tipologie costruttive?

Il 60% circa degli edifici danneggiati aveva da 6 a 20 piani



Seismic Response

Mexico City 1986



- 37 m of very soft clays deposits having Vs= 75 m/s
- tall structures
- big low freq. earthquake

Building fundamental period

≈

Soil resonance period

+

In the Earthquake frequency range

=

DOUBLE RESONANCE EFFECT !

Response seismic analysis

Output
(Local Response
Spectra)

→ Local seismic response
L3
(Vs, G, D, ρ, subsoil model)

→ Norms simplified approach with
Soil classification Vs eq parameter

(admitted only in certain conditions)

Eurocode 8
NTC18

The simplified approach
With soil seismic classification

The
Vs equivalent model
Parameter

$$V_{S,eq} = \frac{H}{\sum_{i=1}^{N} \frac{h_i}{V_{S,i}}}$$

H = depth of the hard bedrock (> 800 m/s)
If deeper than 30m
H = 30

Vs 30

Shear wave velcity Vs model based on the weighted average of the first 30 m of subsoil

H*i* = thickness of the *i* layer

Vs *i* = Vs of the *i* layer

SESMIC SOIL CLASSIFICATION - Ec8 e DM 2018

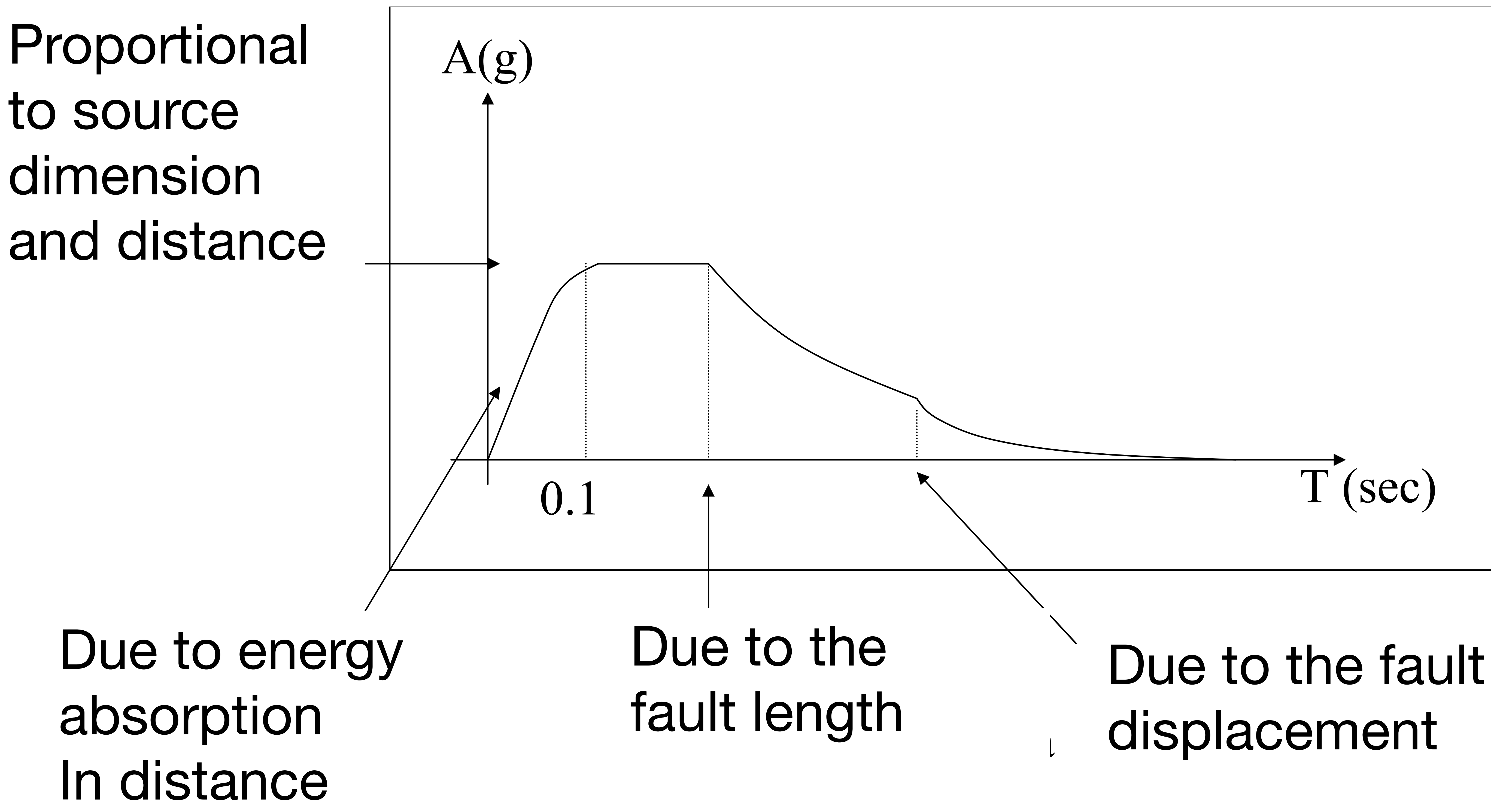
Subsoil class	Description of stratigraphic profile	Parameters		
		$V_{s,30}$ (m/s)	N_{SPT} (bl/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	> 800	–	–
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of m in thickness, characterised by a gradual increase of mechanical properties with depth	360 – 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m	180 – 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with $V_{s,30}$ values of class C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with $V_{s,30}$ > 800 m/s			
S_1	Deposits consisting – or containing a layer at least 10 m thick – of soft clays/silts with high plasticity index (PI > 40) and high water content	< 100 (indicatively)	–	10 - 20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in classes A –E or S_1			

Nspt and Cu Parameters poorly correlated with Vs !

Better use Vs !

Norms Response Spectra

Fault dimension and distance averaged



Vs (30) condition + Topographical conditions

Subsoil class	Description of stratigraphic profile	Parameters		
		$V_{s,30}$ (m/s)	N_{SPT} (bl/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	> 800	–	–
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of m in thickness, characterised by a gradual increase of mechanical properties with depth	360 – 800	> 50	> 250
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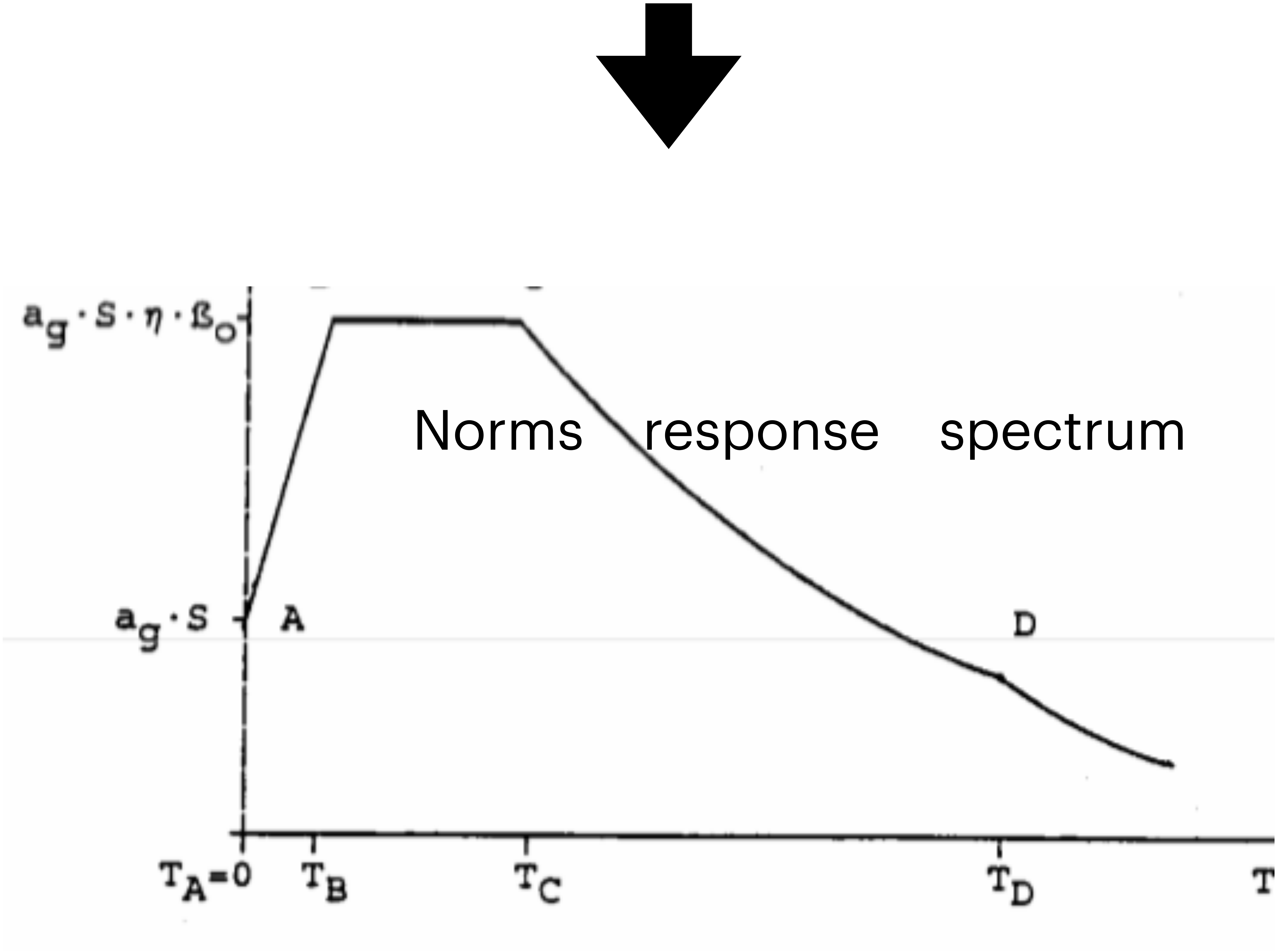
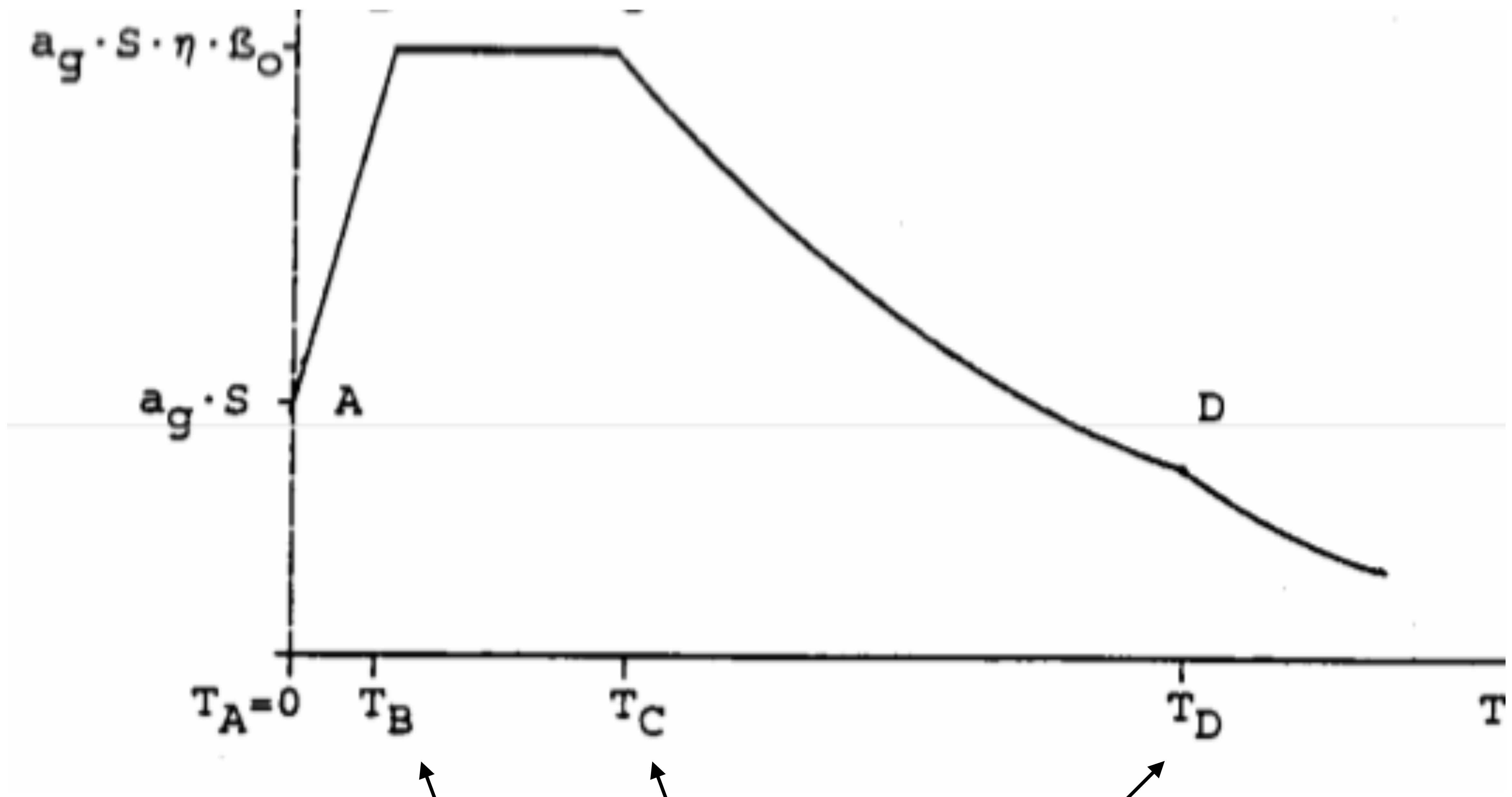
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in classes A –E or S_1			

Categoria	Caratteristiche della superficie topografica
T1	Superficie pianeggiante, pendii e rilievi isolati con inclinazione media i ≤ 15°
T2	Pendii con inclinazione media i > 15°
T3	Rilievi con larghezza in cresta molto minore che alla base e inclinazione media 15° ≤ i ≤ 30°
T4	Rilievi con larghezza in cresta molto minore che alla base e inclinazione media i > 30°



Eurocode 8
NTC18



Different periods

$0 \le T < T_B$ $$S_e(T) = a_g \cdot S \cdot \eta \cdot F_o \cdot \left[\frac{T}{T_B} + \frac{1}{\eta \cdot F_o}\left(1 - \frac{T}{T_B}\right)\right]$$

$T_B \le T < T_C$ $$S_e(T) = a_g \cdot S \cdot \eta \cdot F_o$$

$T_C \le T < T_D$ $$S_e(T) = a_g \cdot S \cdot \eta \cdot F_o \cdot \left(\frac{T_C}{T}\right)$$

$T_D \le T$ $$S_e(T) = a_g \cdot S \cdot \eta \cdot F_o \cdot \left(\frac{T_C \cdot T_D}{T^2}\right)$$

Amplification Factor

Soil Amplification

Topographical Amplification

$$S = S_S \cdot S_T$$

$$\eta = \sqrt{10/(5+\xi)} \ge 0{,}55,$$

Viscous damping (If $\xi \neq 5\%$)

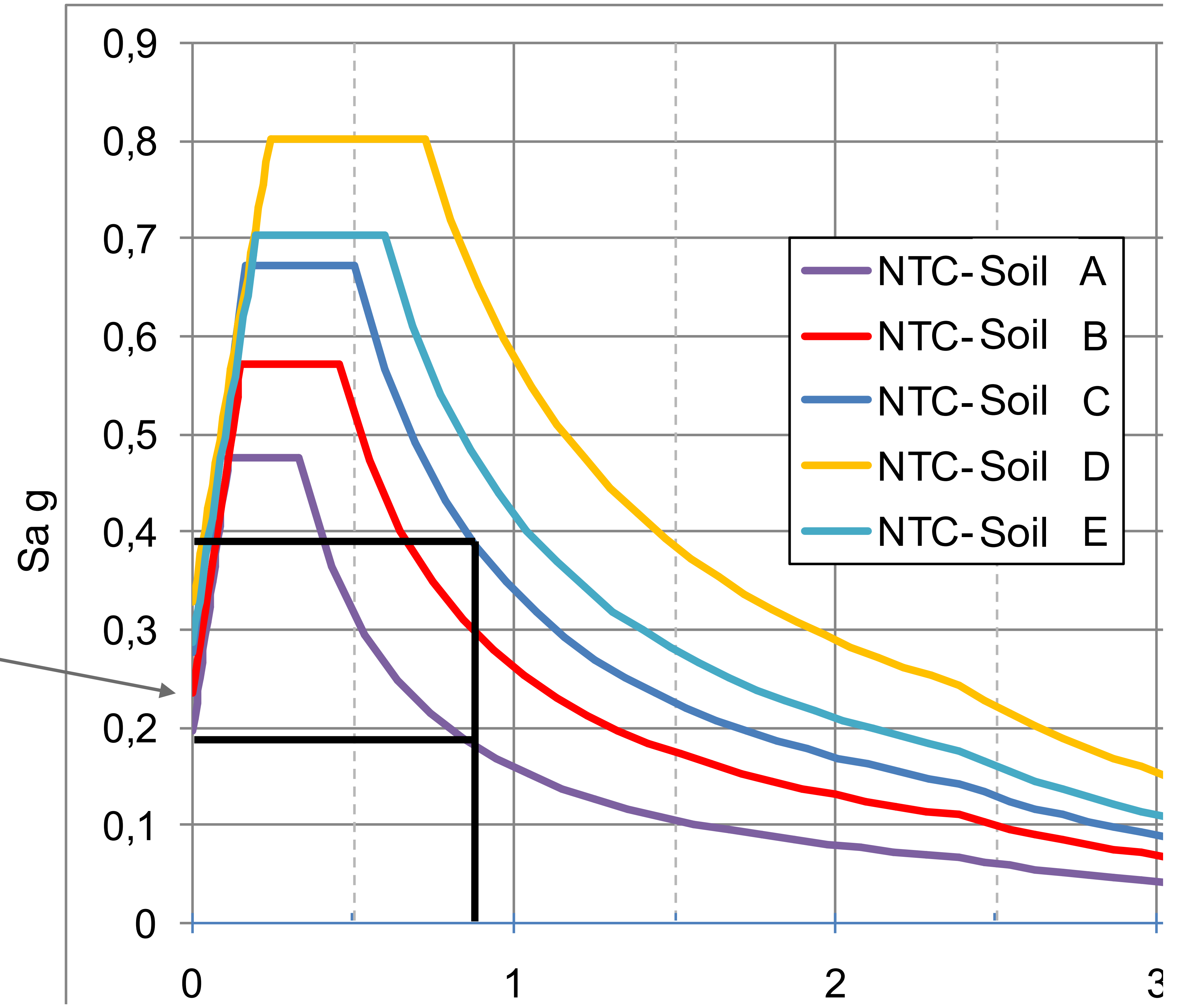
F_O is the maximum spectral amplification on hard bedrock (2.2)

Ag = base hazard site acceletation

NTC 2018 Response spectra

The Euro Norms design some reference spectra called ‘normalised’ on the soil acceleration attended in a certain site for a certain period of return, usually damping ξ is 5%

The spectra vary with the soil type :



A hard rock

B dens soils (Gravers, dense sands)

C medium dense soil (sand, clay)

D low dense soil (Clay, silt, etc)

E Alluvium layers on hard rock

Reference Ag
To starting
Acceleration:

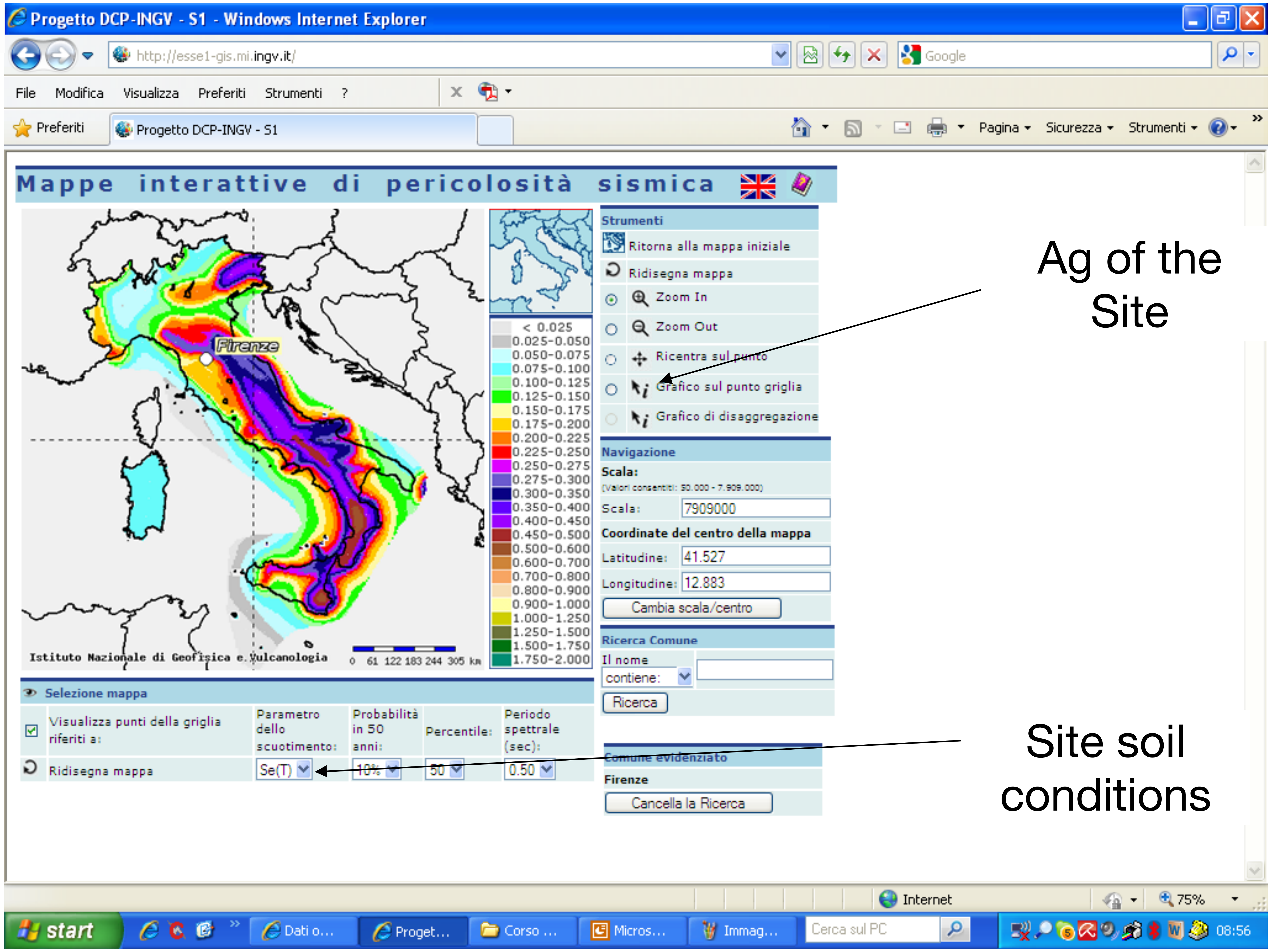
Based on the site
Attended
hazard

(Hazard general map
e.g. 0.2g)

Reference Ag
To starting
Acceleration:

Based on the site
Attended
hazard

(Hazard general map)



Ag of the Site

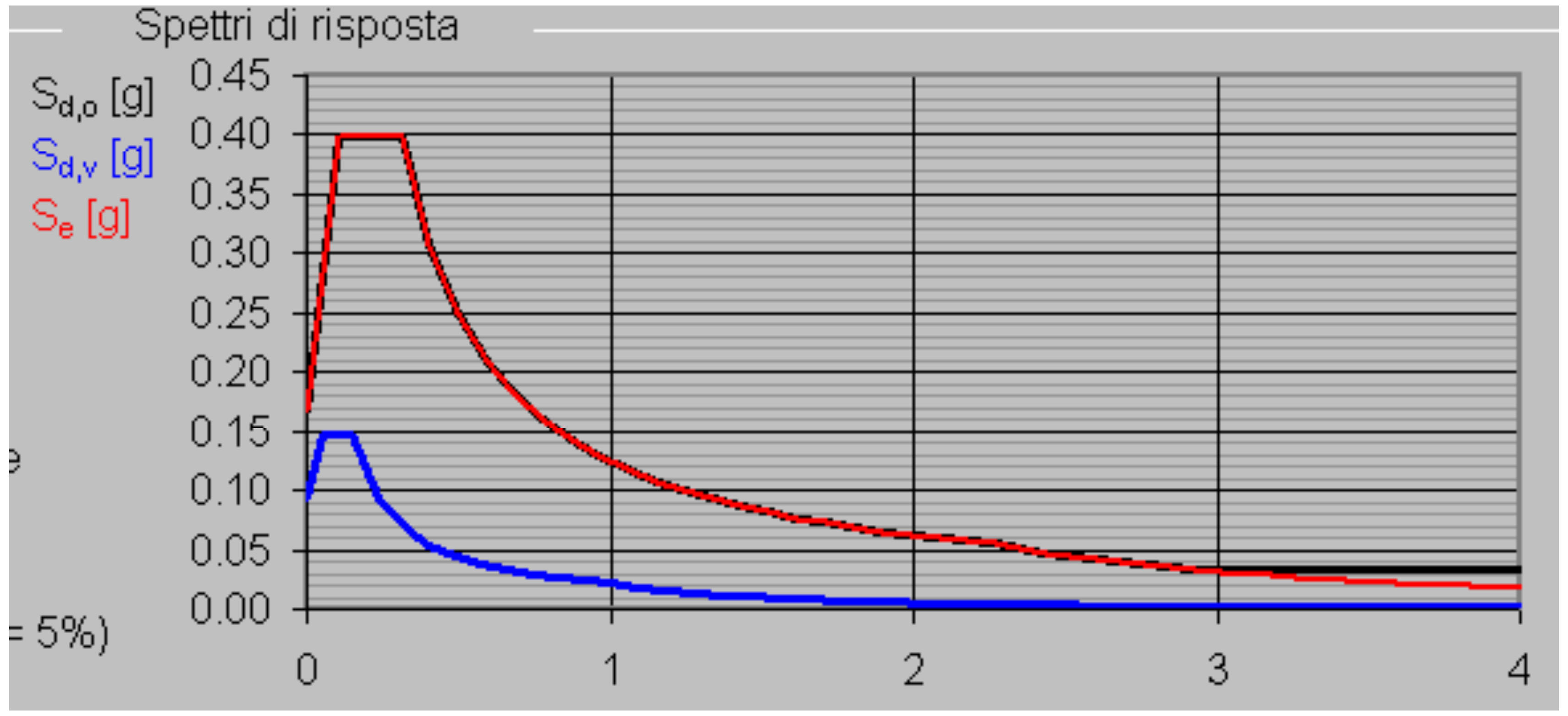
Site soil conditions

WebGIS software to retrieve Ag

Nell’allegato B delle NTC08, vengono forniti i parametri spettrali per ogni punto di una griglia regolare del territorio nazionale e in funzione del cosiddetto “Periodo di Ritorno” (in anni) che a sua volta viene prescritto in funzione di vari parametri (vita attesa dell’edificio, importanza, ecc.)

T_R [anni]	a_g [g]	F_o [-]	T_C^* [s]
30	0.047	2.551	0.253
50	0.056	2.586	0.268
72	0.064	2.594	0.276
101	0.072	2.591	0.282
140	0.080	2.601	0.287
201	0.094	2.524	0.294
475	0.131	2.413	0.302
975	0.167	2.388	0.311
2475	0.221	2.414	0.319

Valori caratteristici dello spettro di risposta elastico per la **Città di Firenze** (*ipotizzandola su basamento sismico affiorante e planare*) e dai quali è possibile calcolare la forma spettrale riportata sotto Orizzontale in rosso e verticale in blu)

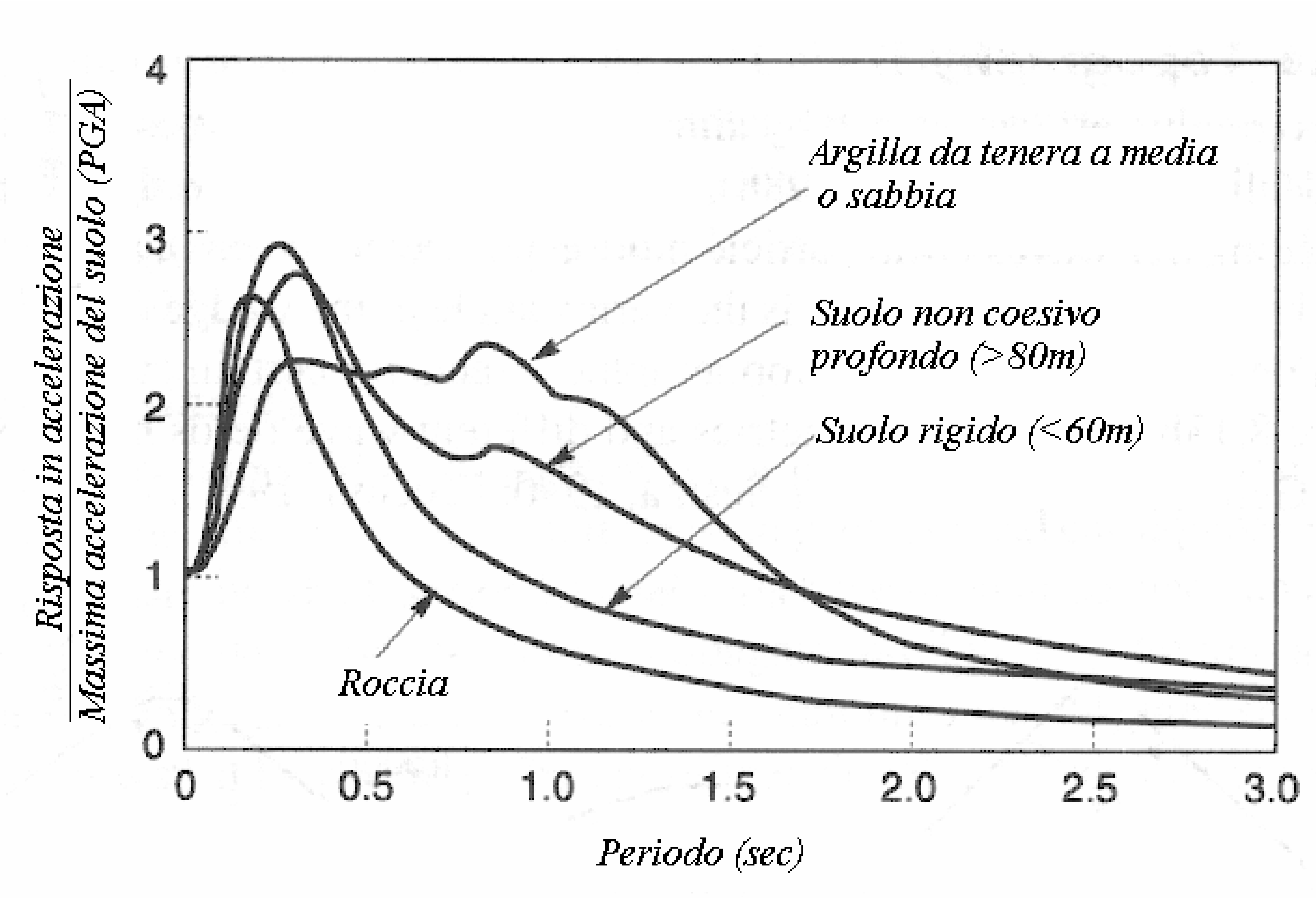


Di fatto, questo spettro di risposta è il terremoto da cui ci dobbiamo difendere

E’ questo il terremoto da utilizzare come moto di input per lo studio di Risposta Sismica Locale

The response spectra (of a free oscillator)

Effetti importanti sugli spettri



1D consideration

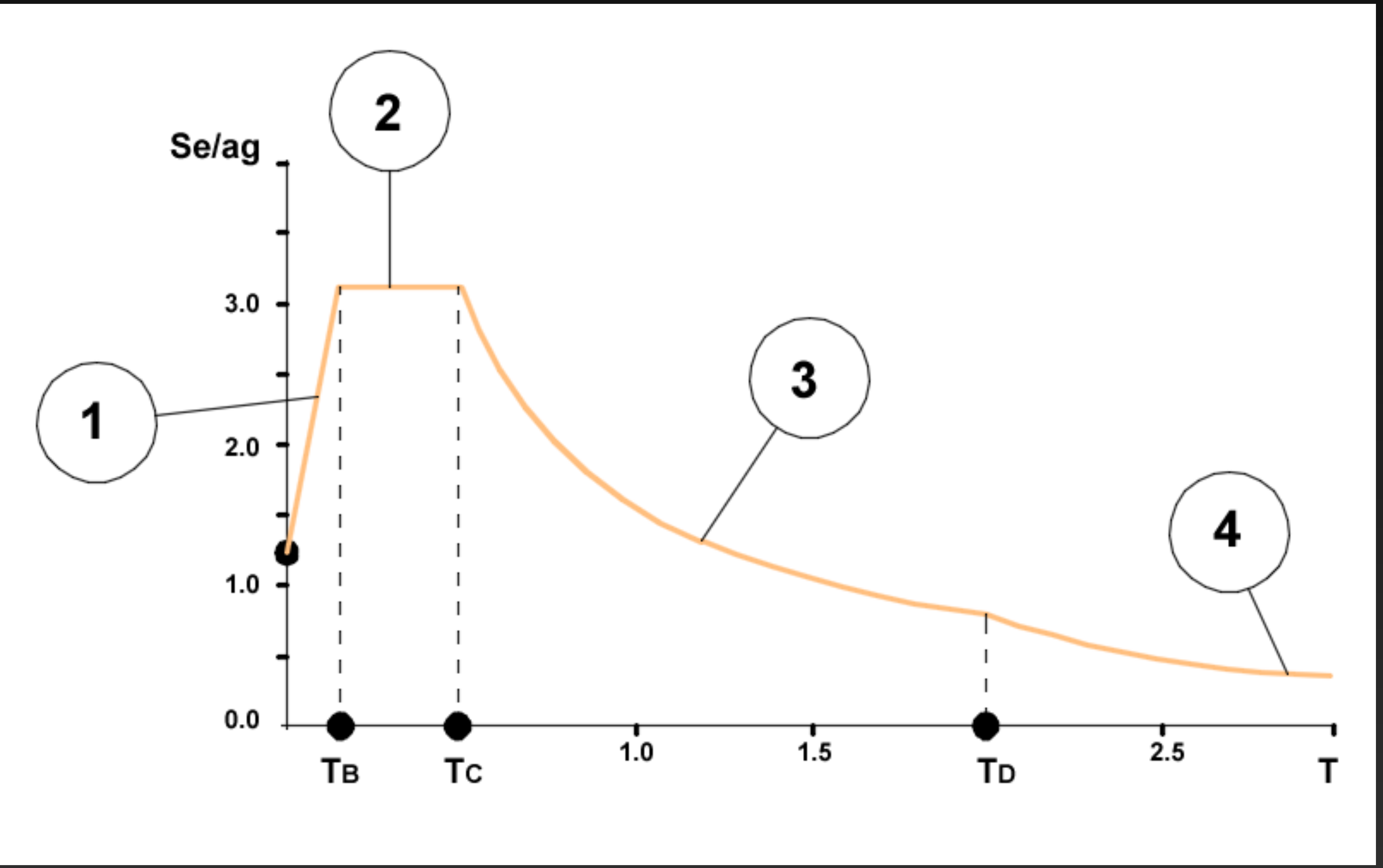
Topographical and lithological factors

Worst (mechanical) soil conditions
=
grater seismic amplification

Tabella 3.2.VI – *Valori del coefficiente di amplificazione topografica S_T*

Categoria topografica	Ubicazione dell'opera o dell'intervento	S_T
T1	-	1,0
T2	In corrispondenza del bordo superiore	1,0÷1,2
T3	In prossimità della cresta	1,0÷1,2
T4	In prossimità della cresta	1,2÷1,4

The Vs eq simplified approach



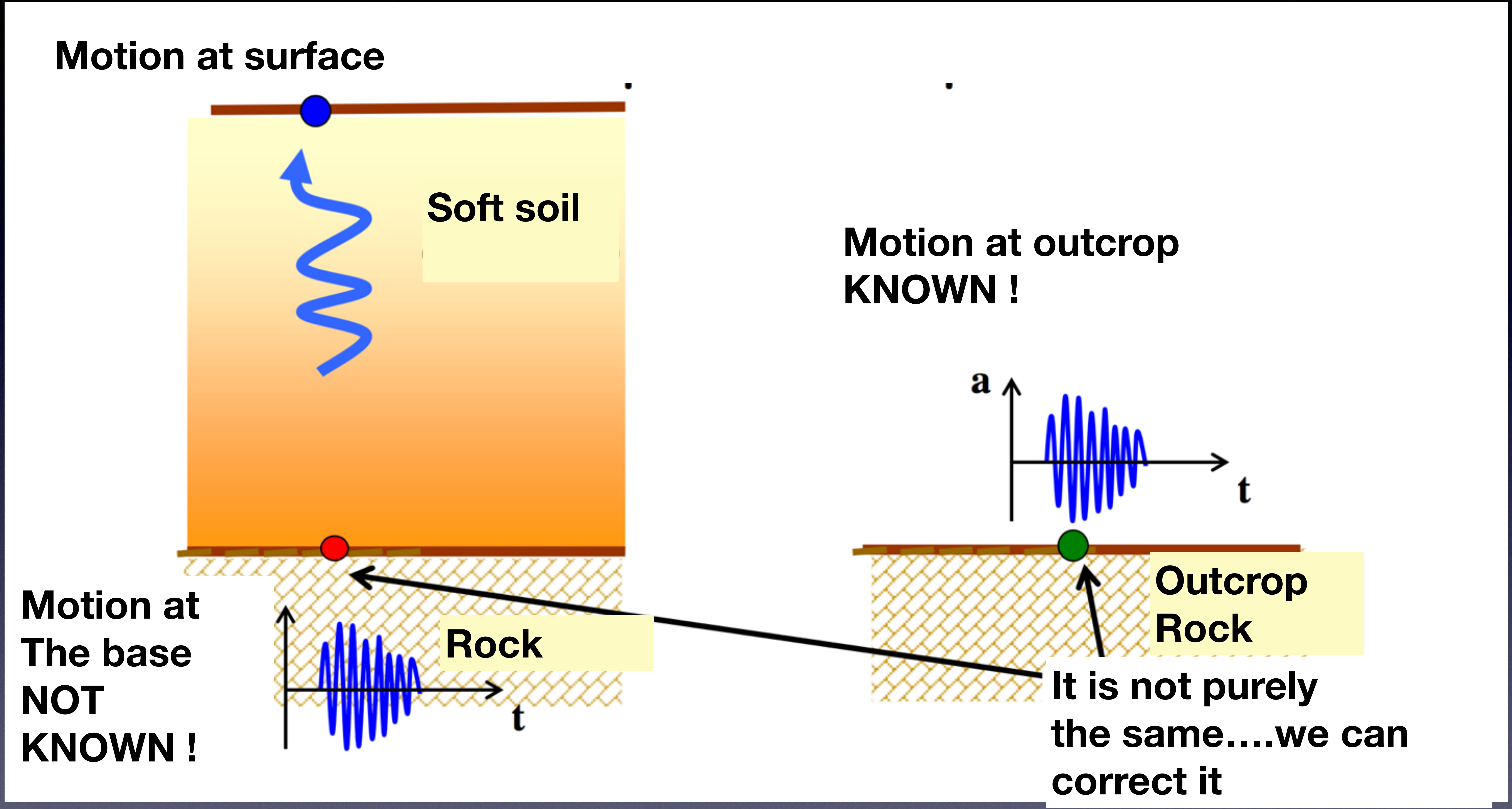
- Where we are (hazard map Ag_0)
- Topographical condition
- Vs $_{(30)}$ condition

Several free software to design the reference Norms Spectrum

The Seismic Input selection

for the L3 deterministic level

The seismic input choice



Seismic Input choice

The use of accelerograms

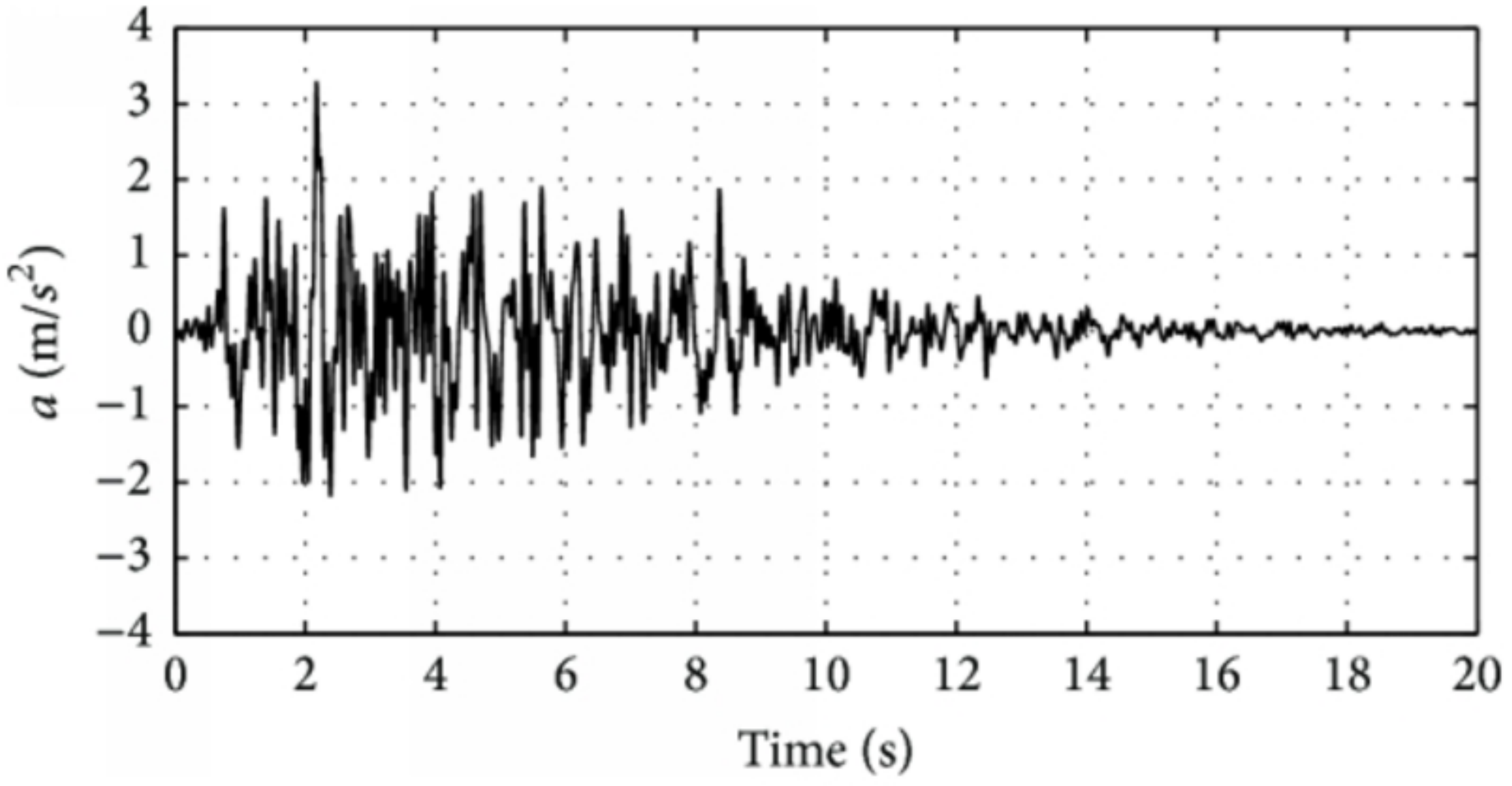
Seismic local response need seismic timeseries. These can be:

Artificial : generated with stochastic algorithms

Synthetics; modelling numerically the fault rupture

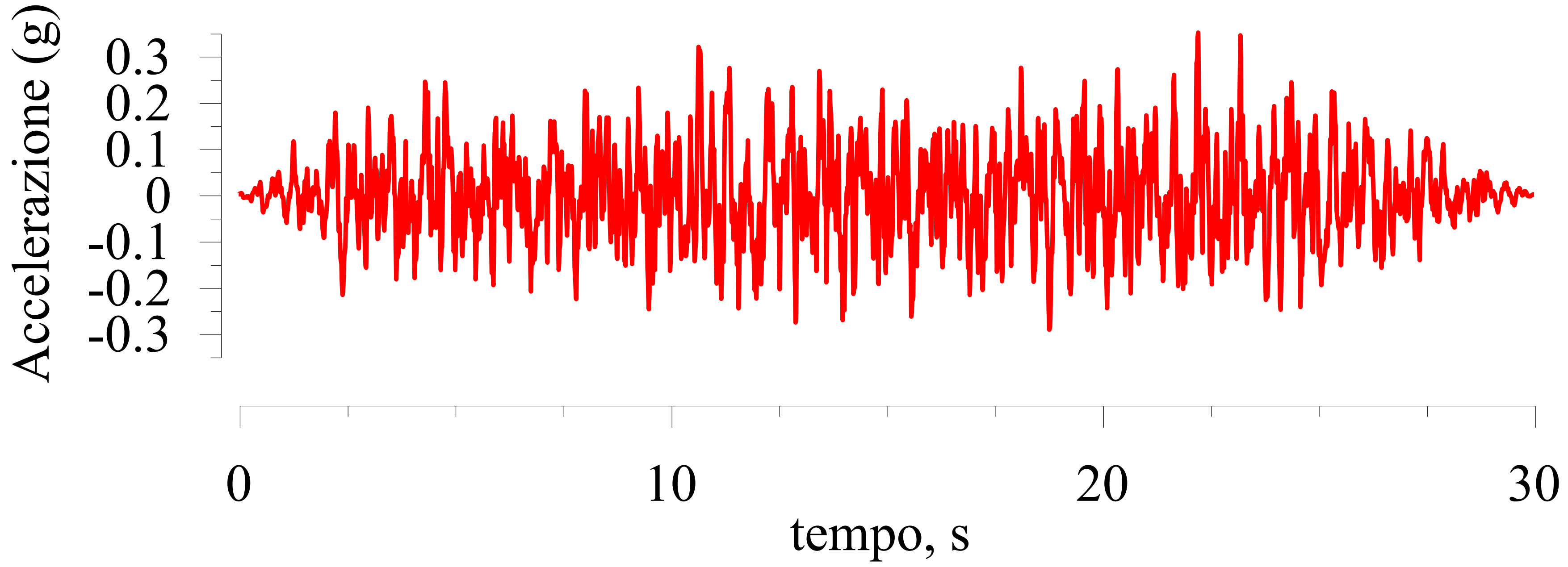
Real : real seismic records

The real ones are the preferred

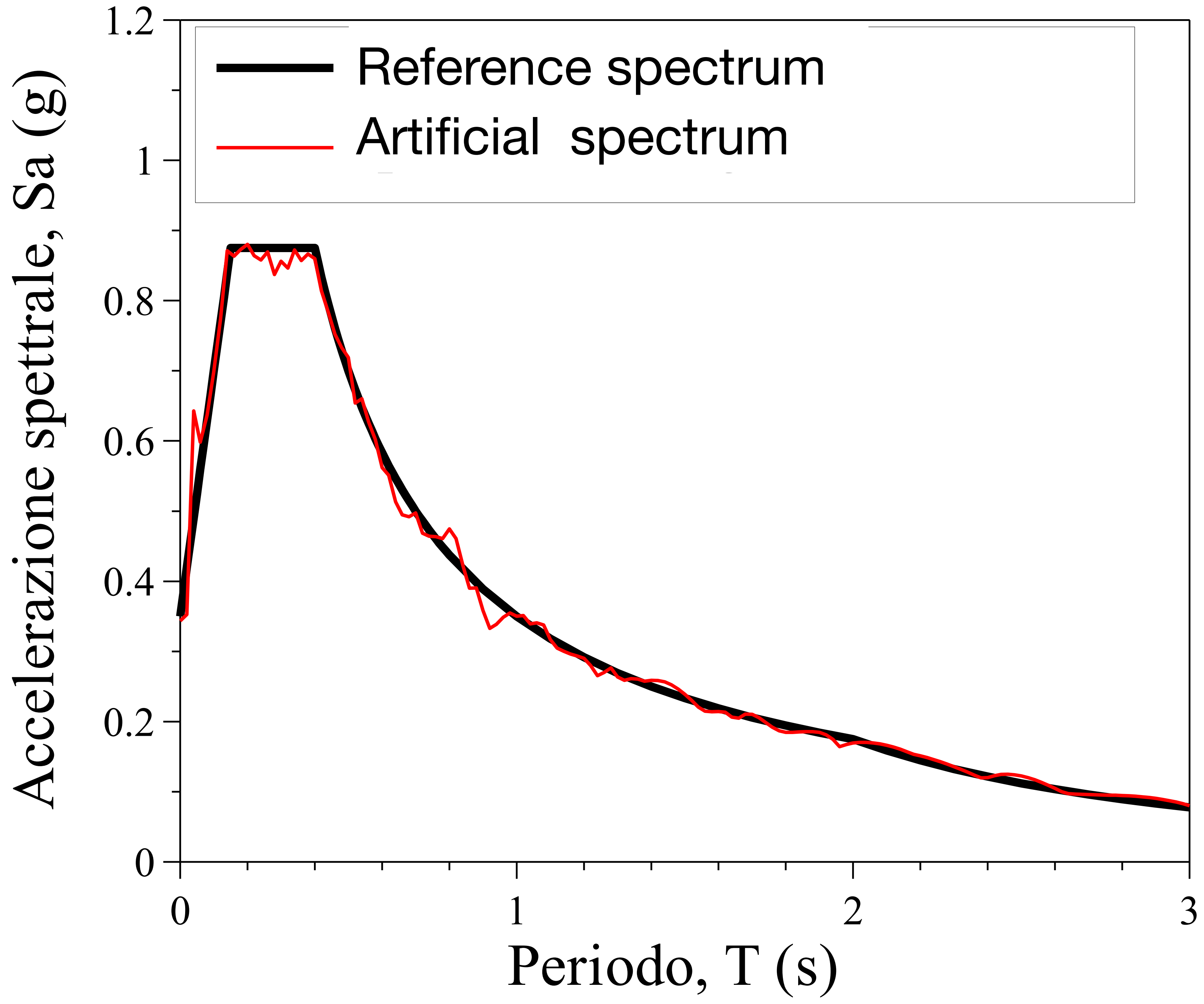


Seismic Input choice

Artificial : generated with stochastic algorithms, must be compatible with reference target spectra (e.g. SIMQE, BELFAGOR codes)

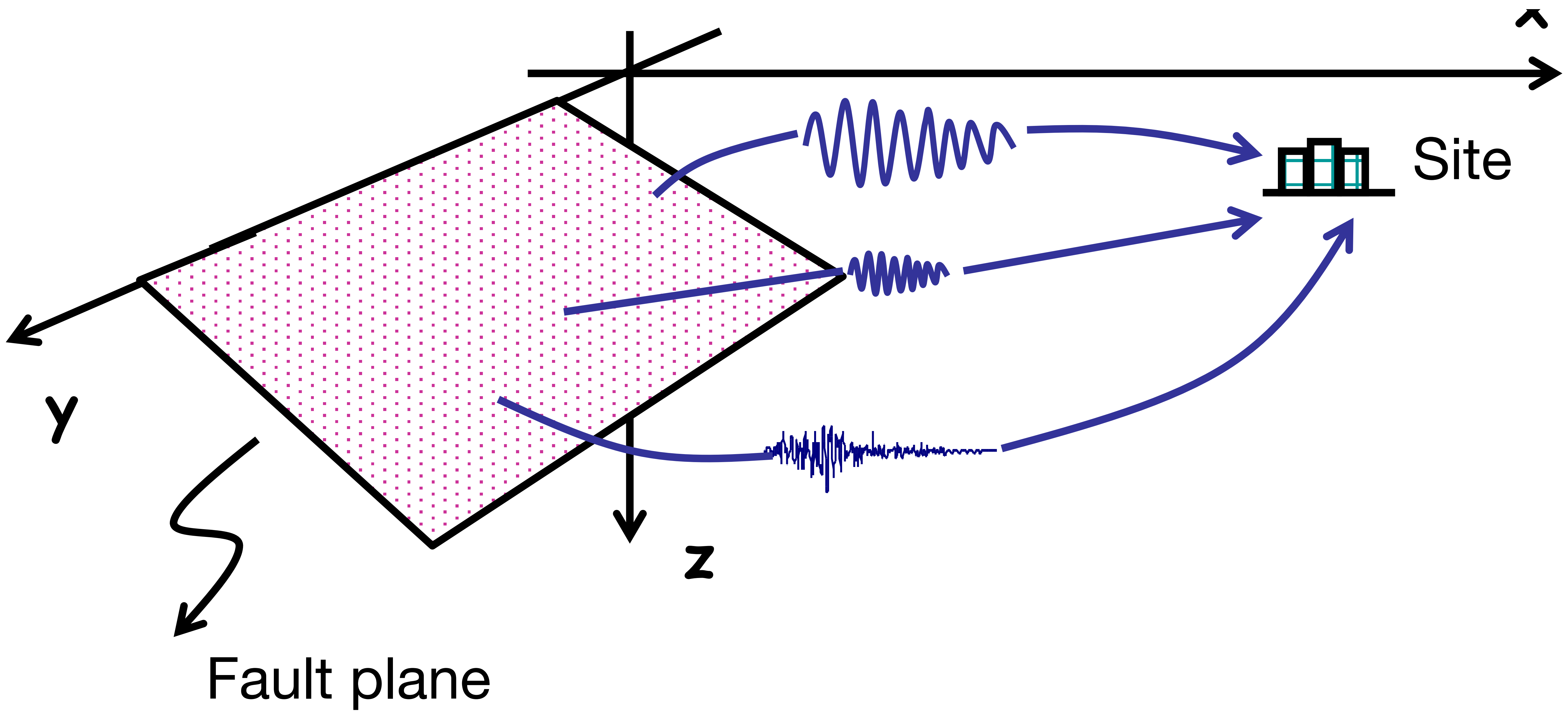


Artificial computed accelerogram



Seismic Input choice

Synthetics : Numerical model of the fault rupture



Base rupture parameters are difficult to asses…..

Seismic Input choice

Real accelerograms recorded in world database

USA

Pacific Earthquake Engineering Research Center (**PEER**)
http://peer.berkeley.edu/smcat
COSMOS http://db.cosmos-eq.org
California Geological Survey ftp://ftp.consrv.ca.gov/pub/dmg/csmip/

Japan

Kyoshin Net (**K-NET**)
http://www.k-net.bosai.go.jp

Europe

European Strong Motion Database (**ESD**)
http://www.isesd.hi.is/ESD_Local/frameset.htm

Italy

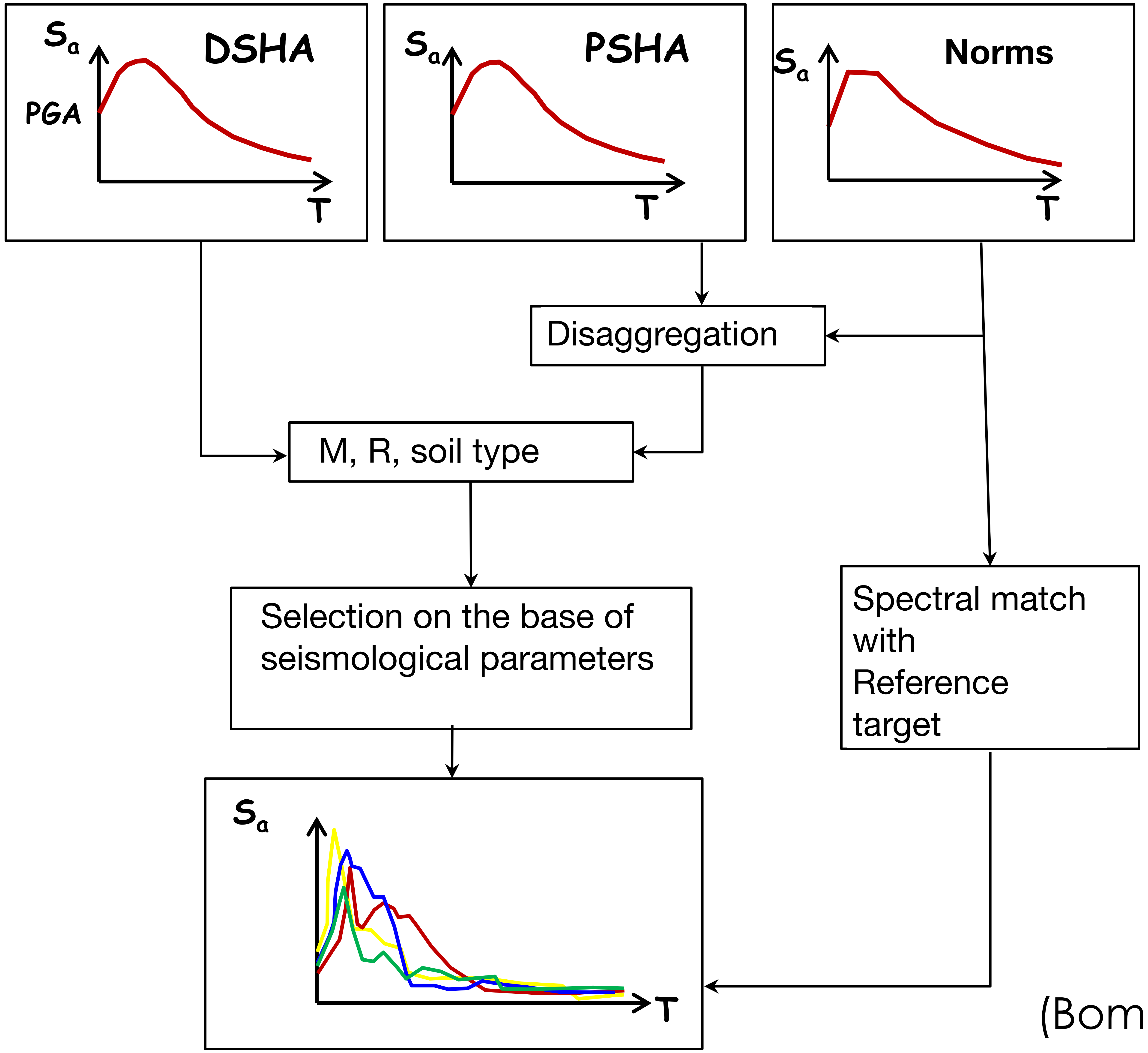
Italian Accelerometric Archive (**ITACA**) http://itaca.mi.ingv.it/
Site of Italian Strong-Motion Accelerograms (**SISMA**)
http://sisma.dsg.uniroma1.it

Rexel *Iervolino et al*

Spectrum-Compatibility Approach

Seismic Input choice

Diagram of spectra research



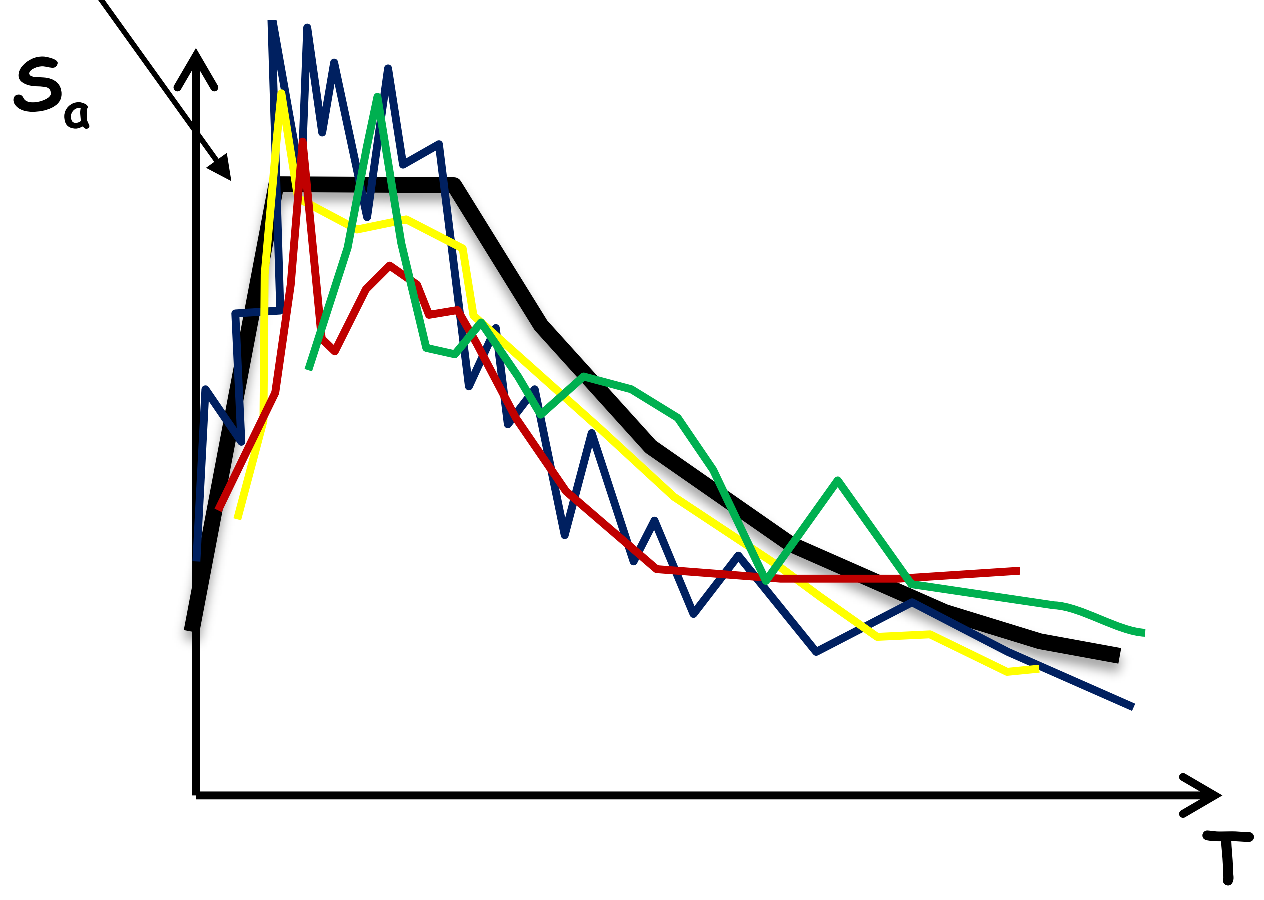
Find in the database the Real accelerograms who best fit my target reference spectrum for that specific site

(Bommer & Acevedo, 2004)

Seismic Input choice

Spectrum compatibility

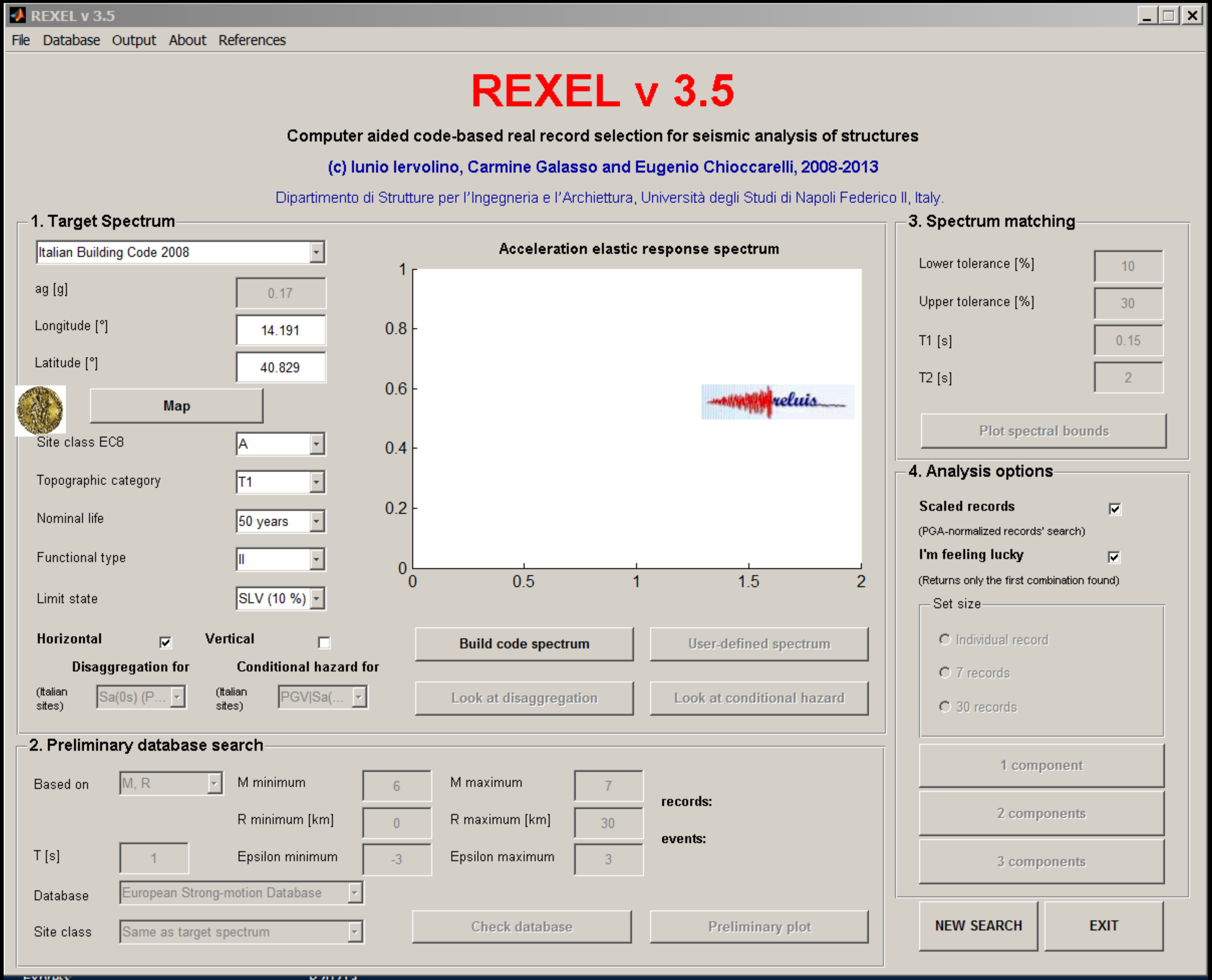
We want to select several inputs (3-7), with the average spectrum that satisfy the compatibility with the target one



Seismic Input choice

Rexel *Iervolino et al*

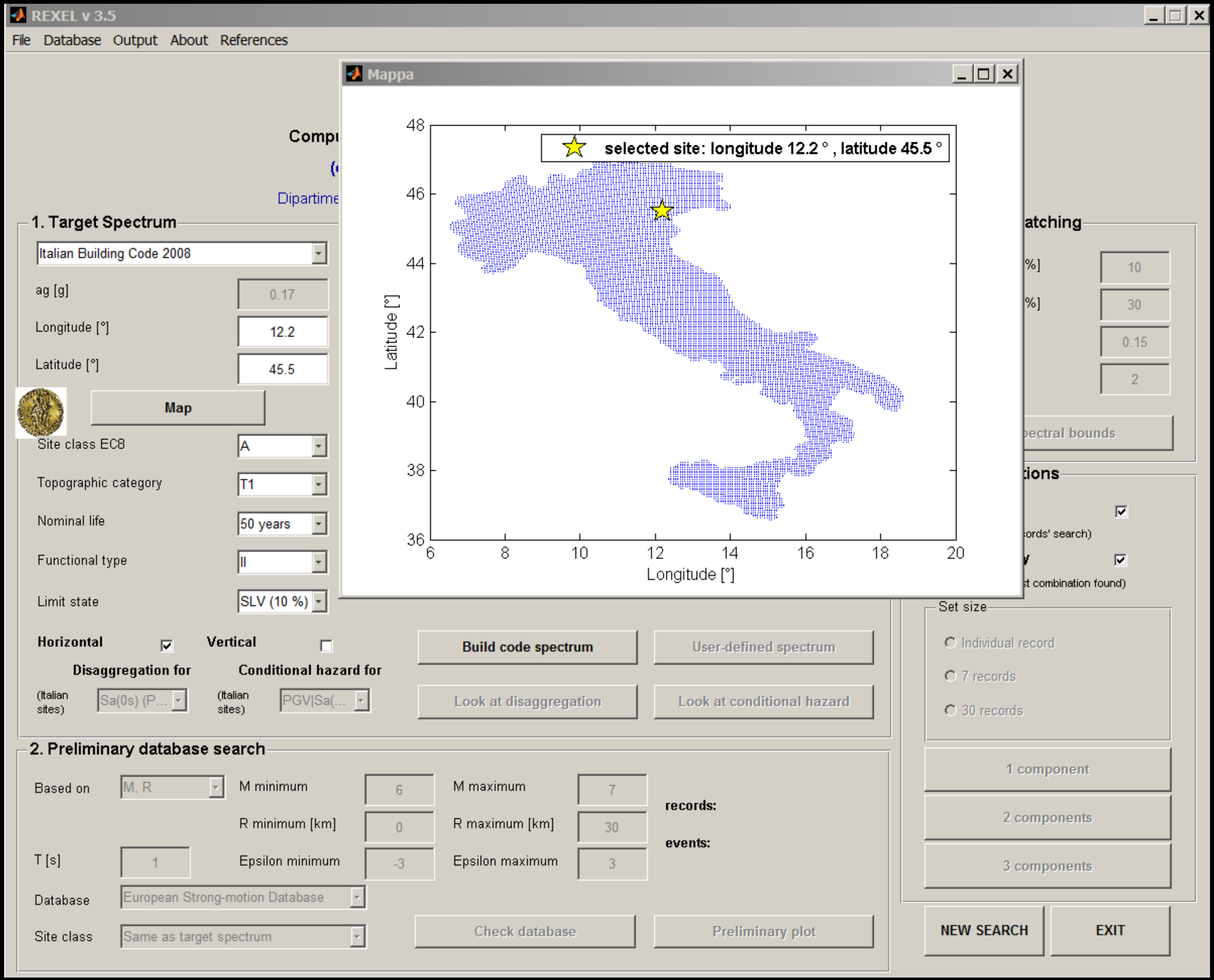
Free software
For
Accelerogram
selection



Seismic Input choice

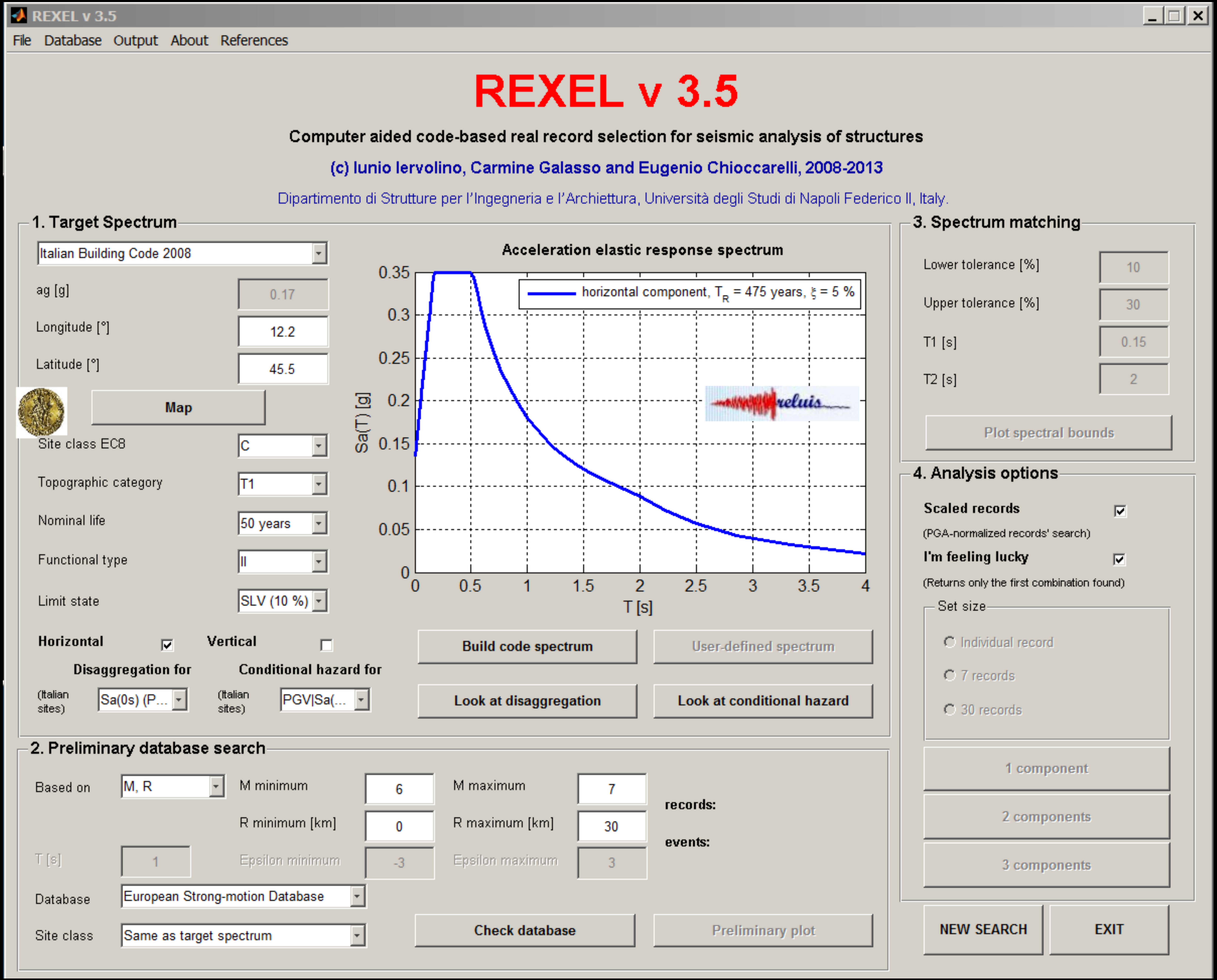
Rexel *Iervolino et al*

1) Chose the site: es. Padova



Seismic Input choice

Rexel *Iervolino et al*



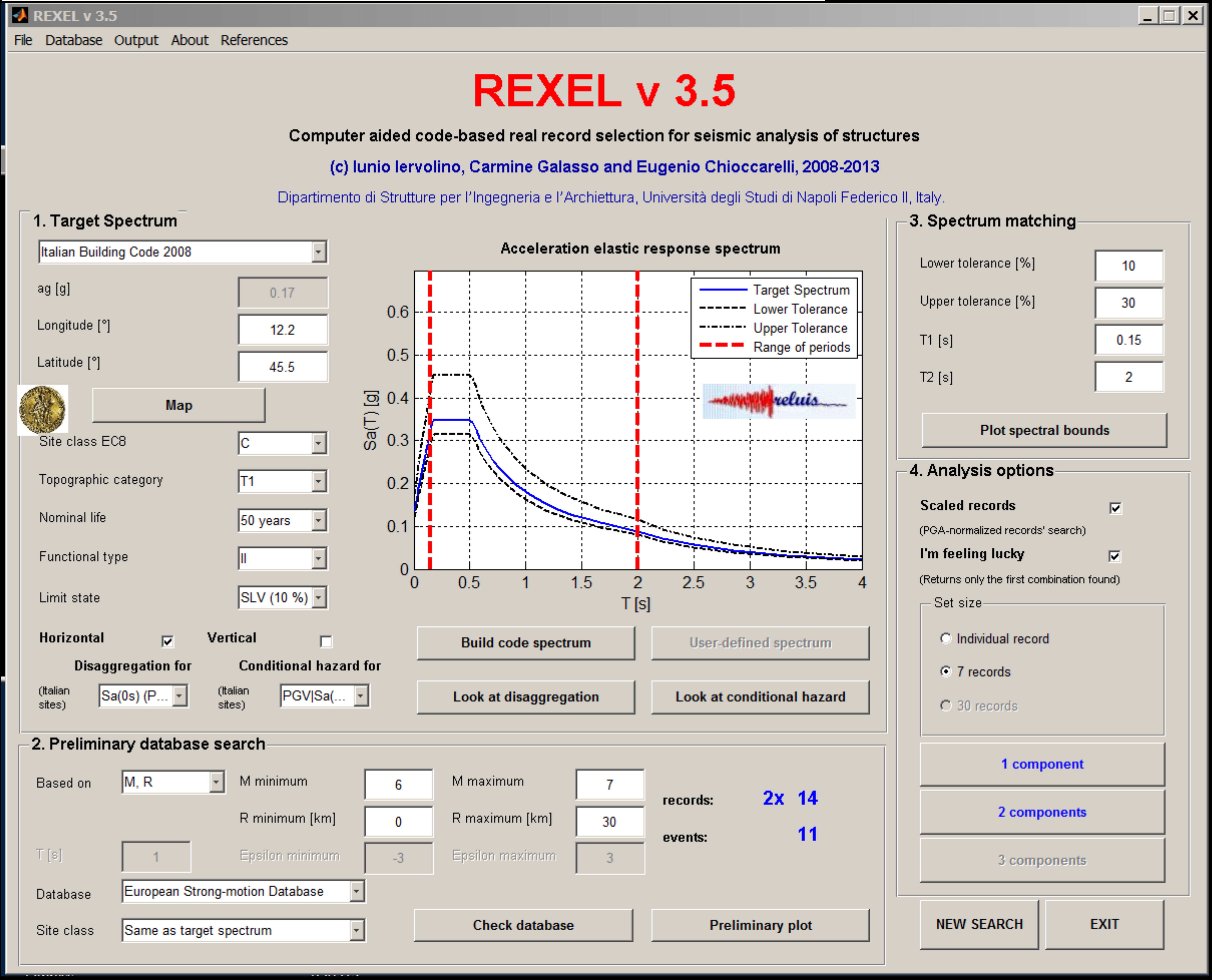
2) Select the reference spectrum for the selected site

Function of V_{S30} class, topography, Period of return, Etc.

Seismic Input choice

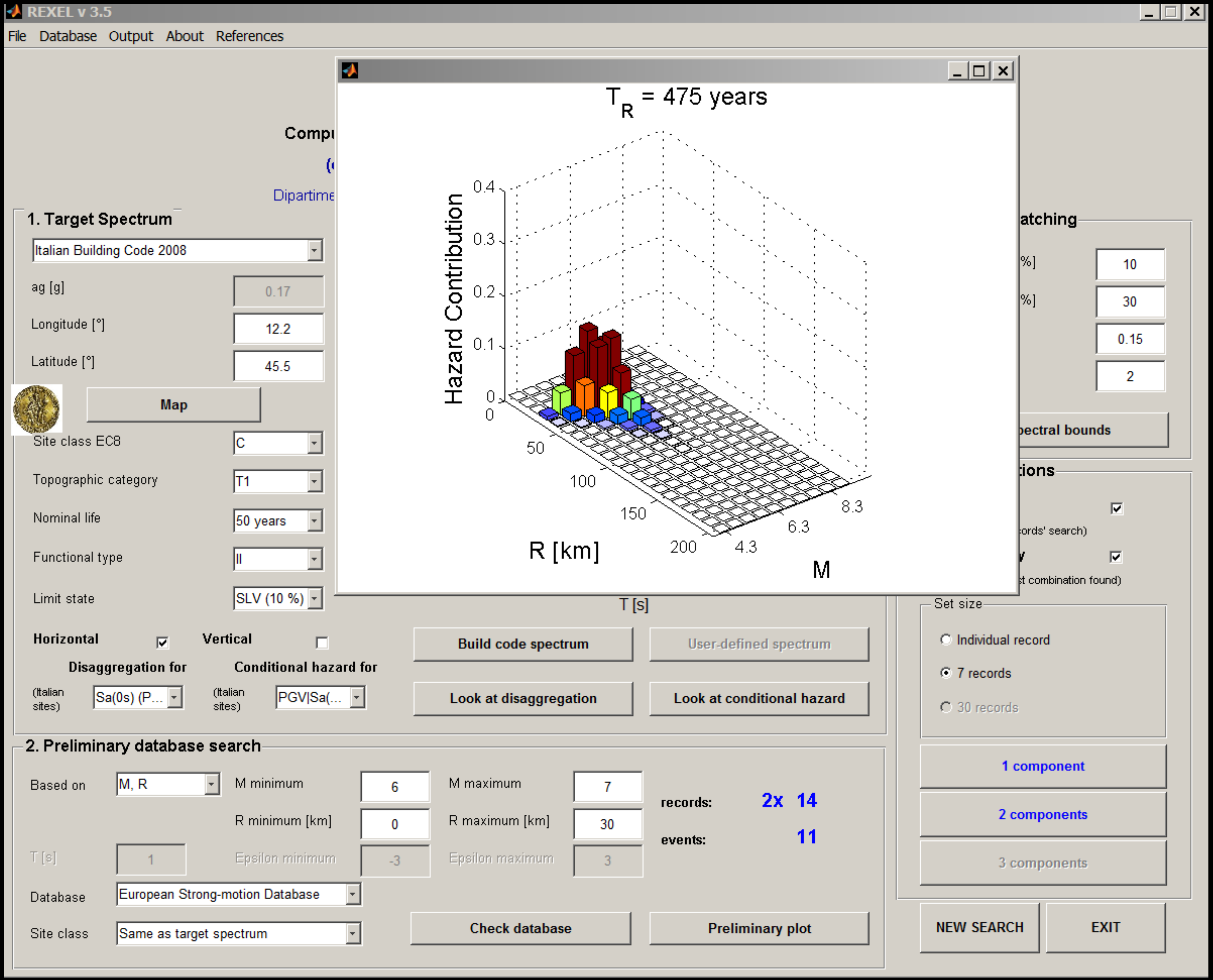
Rexel *Iervolino et al*

3) chose the magnitude and distance of the source and the confidence interval around the reference spectrum



Seismic Input choice

Rexel *Iervolino et al*



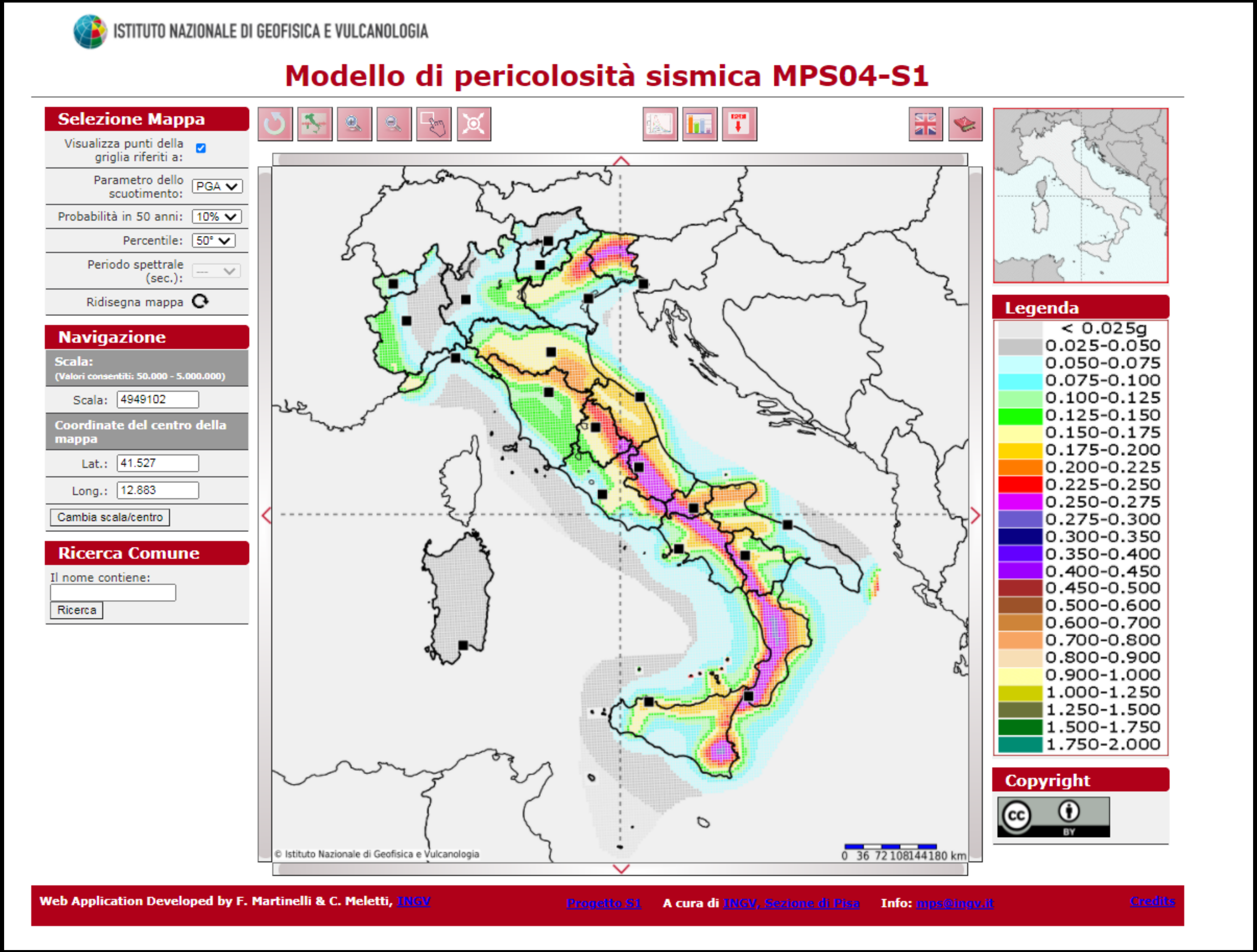
chose the magnitude and distance is crucial !

How to chose them ?

Seismic Input choice

Select the site
General hazard Map
With the considered Period of return

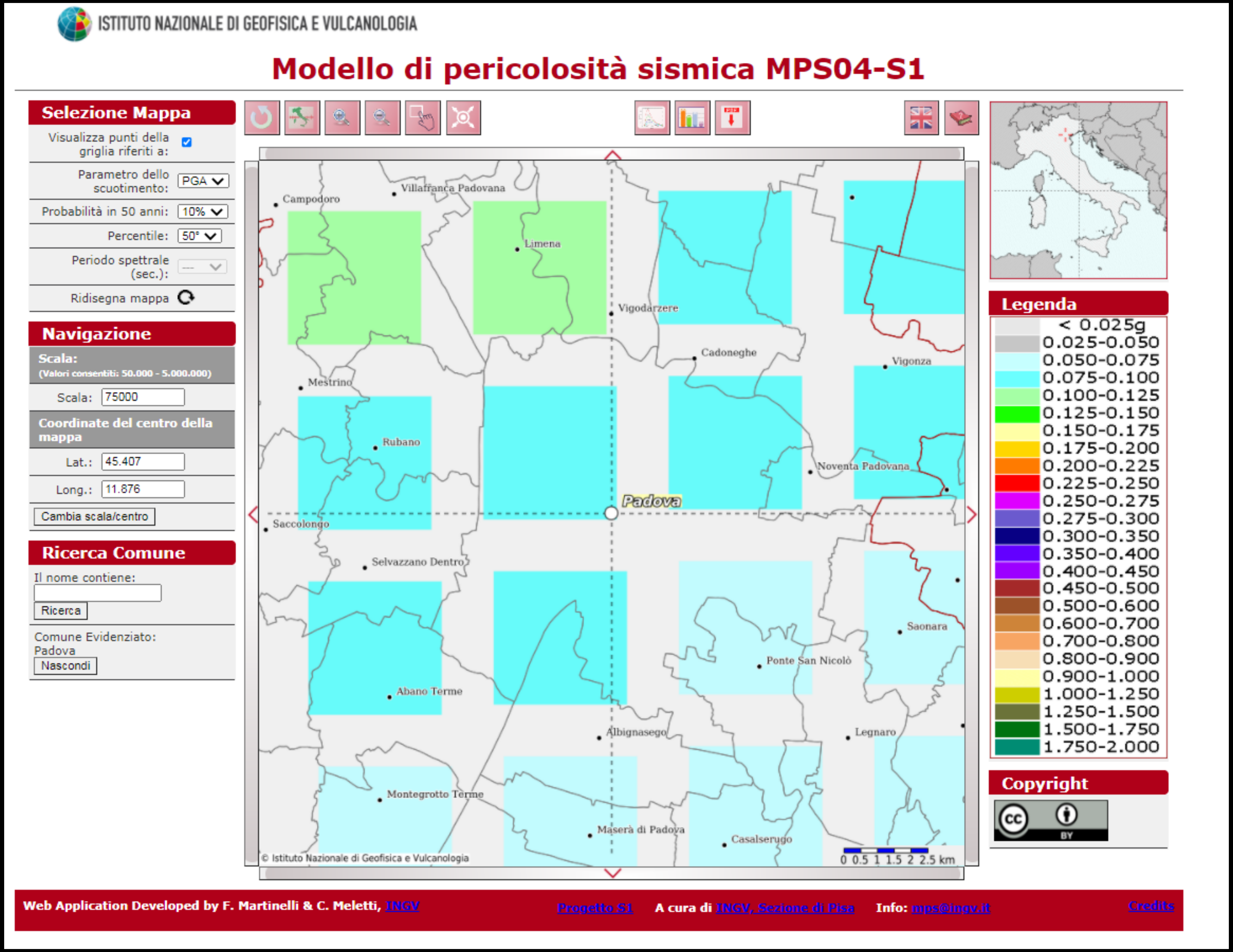
e.g. 475 yers, 10 % exc. in 50 years



esse-1.ingv.mi.it

Seismic Input choice

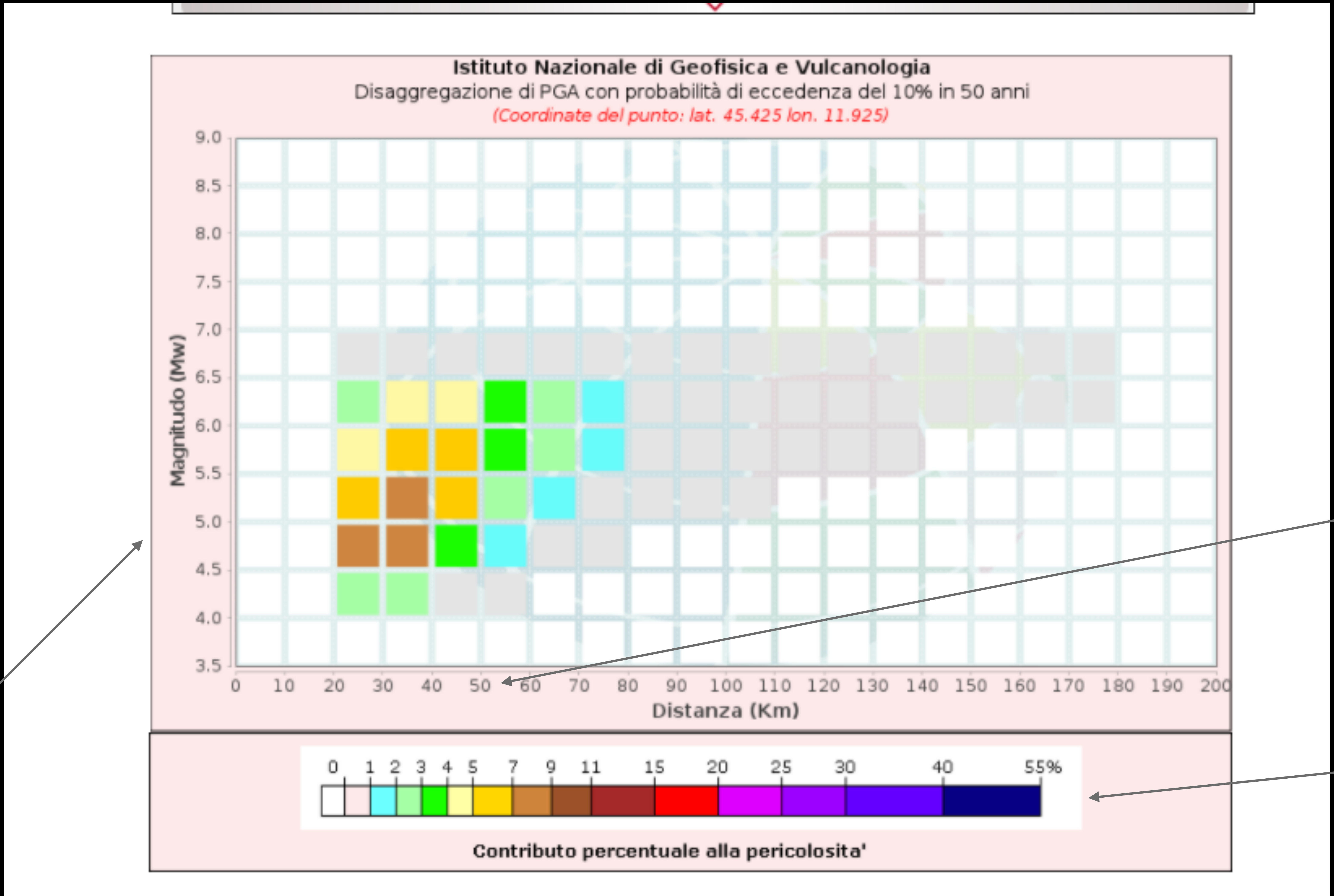
Select the Ag site point of interest



Seismic Input choice

Look to the Desegregation:

Magnitude anf Distance contribution to the effect



Magnitude

Distance

Contribution to The hazard

Disaggregazione di PGA con probabilità di eccedenza del 10% in 50 anni (Coordinate del punto: lat. 45.425 lon. 11.925)											
Distanza (Km)	Magnitudo (Mw)										
	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	6.5-7.0	7.0-7.5	7.5-8.0	8.0-8.5	8.5-9.0
0-10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
10-20	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
20-30	0.0000	2.9600	7.4100	6.0800	4.0300	2.2200	0.2820	0.0000	0.0000	0.0000	0.0000
30-40	0.0000	2.2200	7.3100	7.9400	6.6900	4.5700	0.6590	0.0000	0.0000	0.0000	0.0000
40-50	0.0000	0.5390	3.4700	5.1900	5.3900	4.4000	0.7050	0.0000	0.0000	0.0000	0.0000
50-60	0.0000	0.0048	1.1200	2.9600	3.7900	3.6100	0.6330	0.0000	0.0000	0.0000	0.0000
60-70	0.0000	0.0000	0.1570	1.3300	2.2500	2.4700	0.4710	0.0000	0.0000	0.0000	0.0000
70-80	0.0000	0.0000	0.0026	0.5790	1.4600	1.6100	0.3170	0.0000	0.0000	0.0000	0.0000
80-90	0.0000	0.0000	0.0000	0.1650	0.8270	0.9850	0.2030	0.0000	0.0000	0.0000	0.0000
90-100	0.0000	0.0000	0.0000	0.0264	0.4570	0.6320	0.1370	0.0000	0.0000	0.0000	0.0000
100-110	0.0000	0.0000	0.0000	0.0002	0.2200	0.4080	0.0940	0.0000	0.0000	0.0000	0.0000
110-120	0.0000	0.0000	0.0000	0.0000	0.0773	0.2490	0.0639	0.0000	0.0000	0.0000	0.0000
120-130	0.0000	0.0000	0.0000	0.0000	0.0220	0.1580	0.0466	0.0000	0.0000	0.0000	0.0000
130-140	0.0000	0.0000	0.0000	0.0000	0.0054	0.1440	0.0493	0.0000	0.0000	0.0000	0.0000
140-150	0.0000	0.0000	0.0000	0.0000	0.0001	0.0810	0.0339	0.0000	0.0000	0.0000	0.0000
150-160	0.0000	0.0000	0.0000	0.0000	0.0000	0.0355	0.0195	0.0000	0.0000	0.0000	0.0000
160-170	0.0000	0.0000	0.0000	0.0000	0.0000	0.0130	0.0097	0.0000	0.0000	0.0000	0.0000
170-180	0.0000	0.0000	0.0000	0.0000	0.0000	0.0016	0.0017	0.0000	0.0000	0.0000	0.0000
180-190	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
190-200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

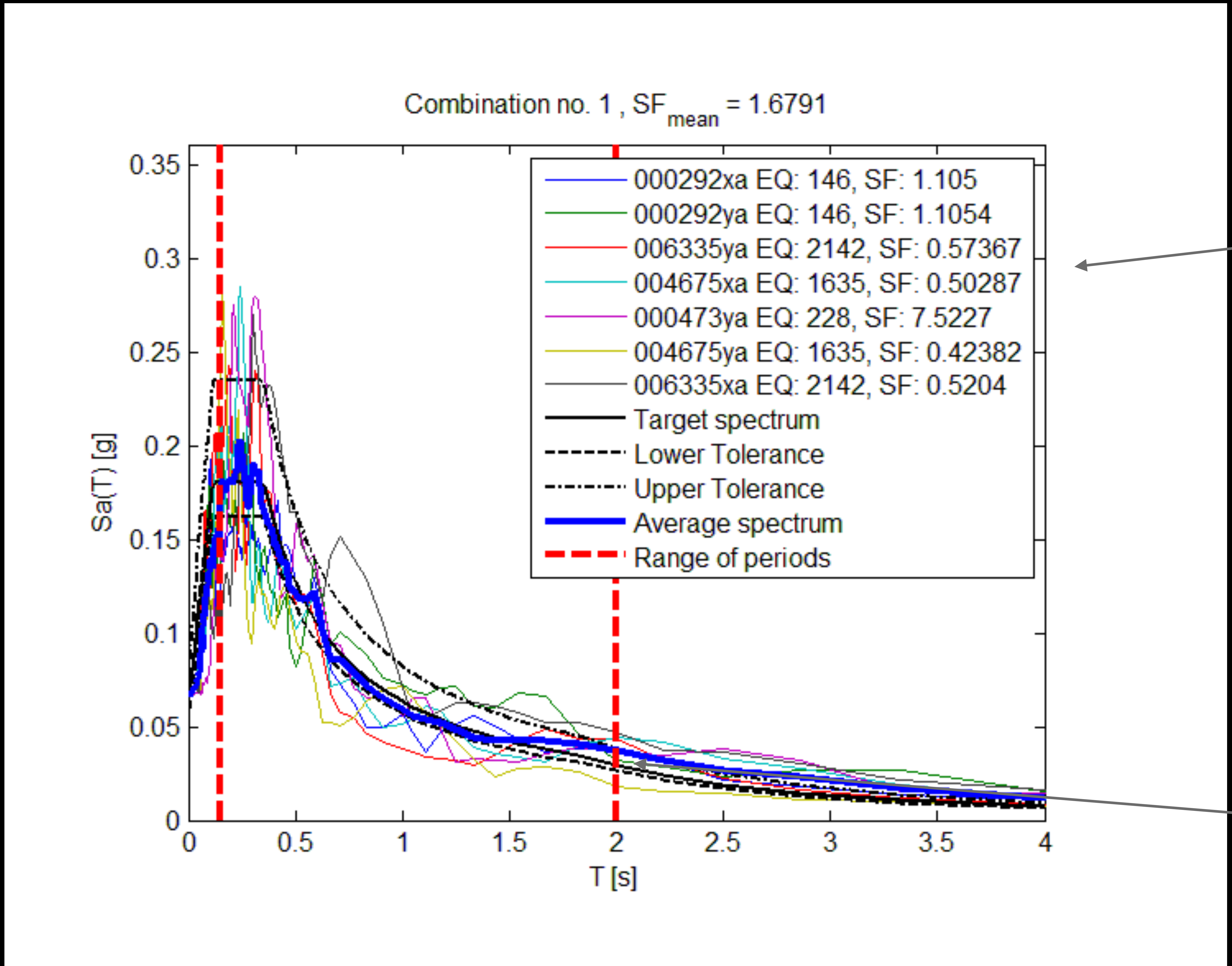
Valori Medi		
Magnitudo	Distanza	Epsilon
5.5	44.0	1.53

The distribution must fit with the spectra research compatibility

Seismic Input choice

Rexel *Iervolino et al*

Results of the accelerograms selection

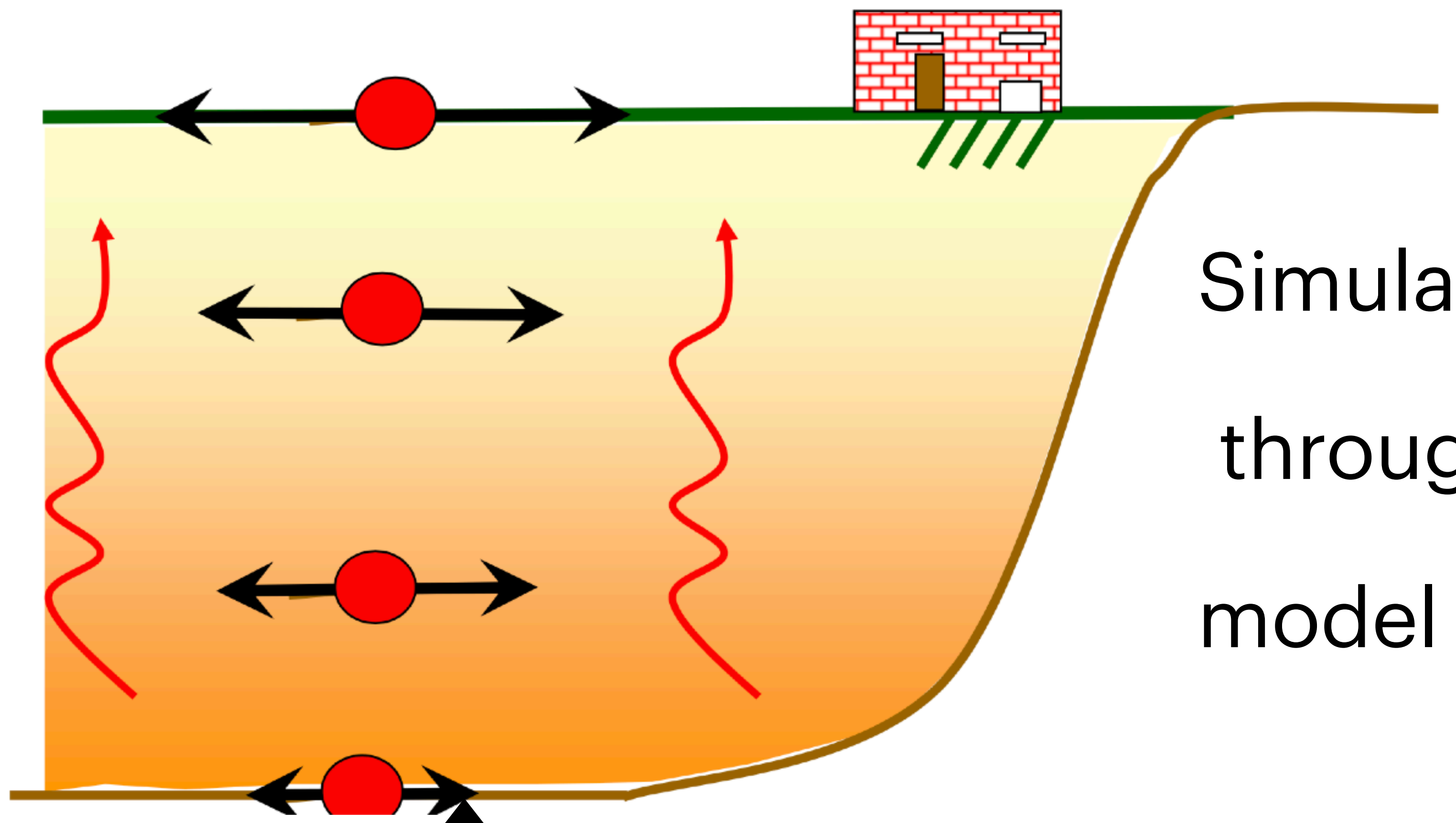


7 real spectrum-compatible accelerograms (<u>scaled</u>)

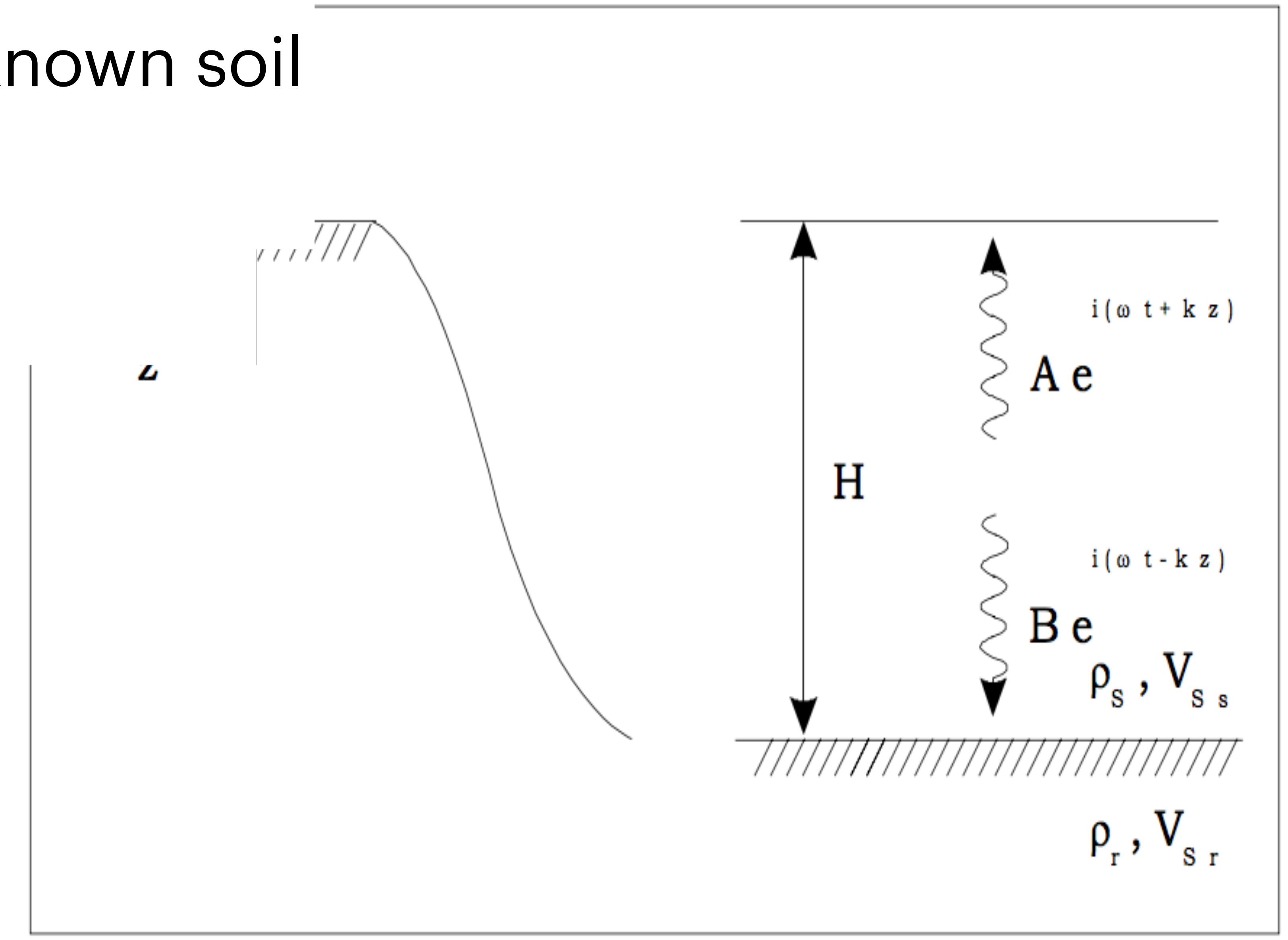
Selected as input for LSR

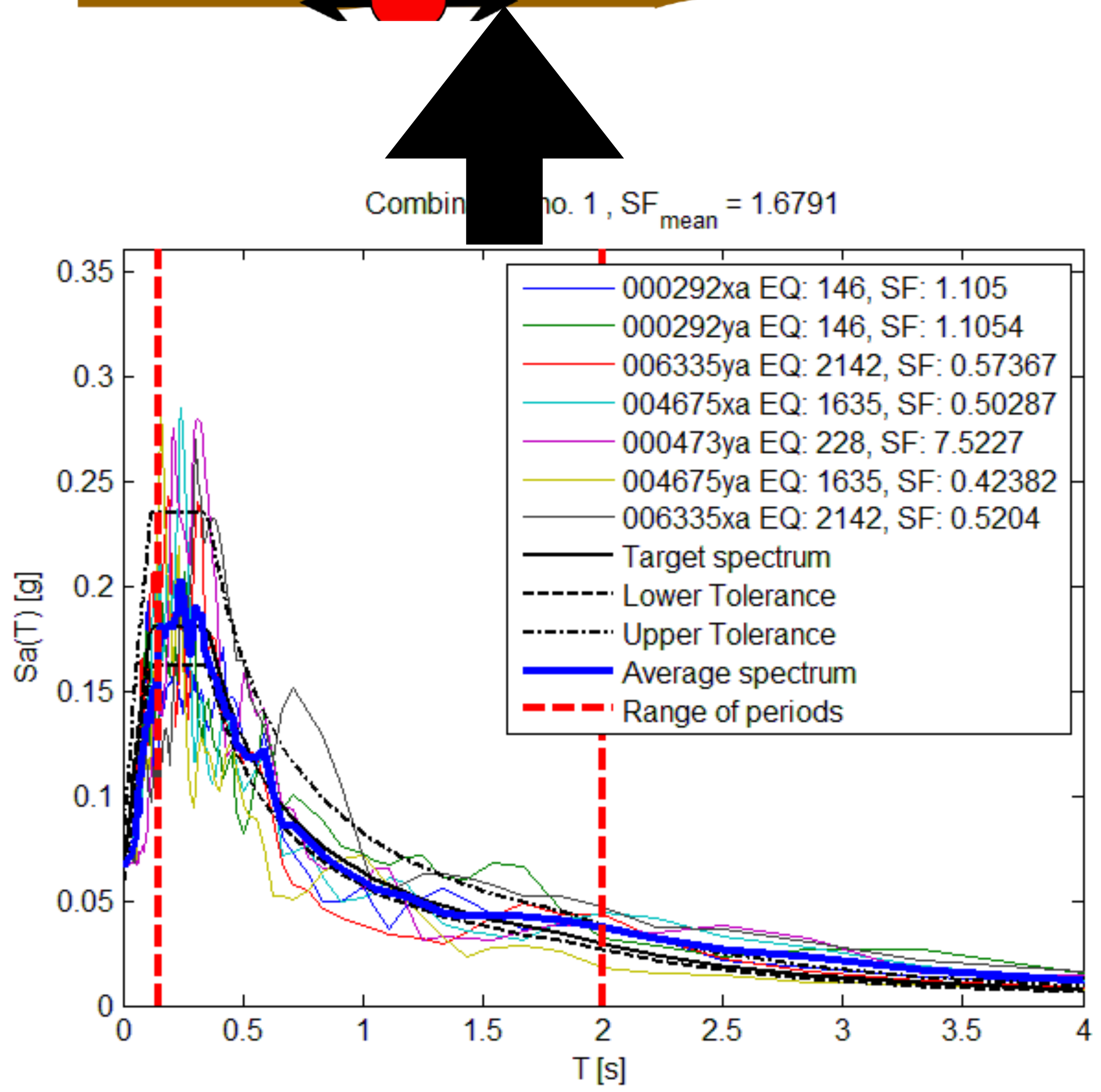
Reference Norms Spectrum

Numerical methods for Seismic response analysis



Simulate the motion through a known soil model





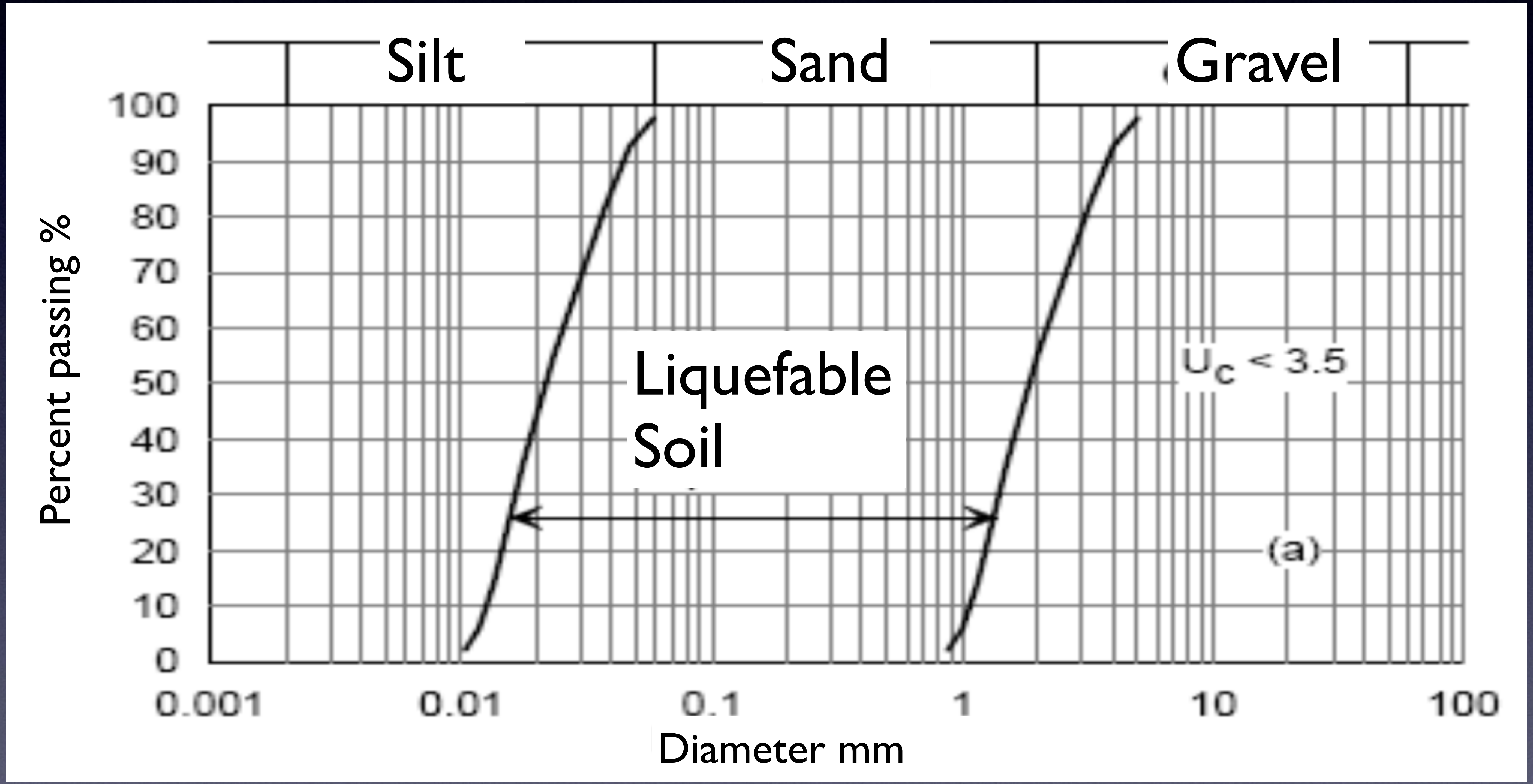
Seismic Induced Effects

- Instabilities
- Collapse
- Landslides

- LIQUEFACTION

Induced effect: Liquefaction

Liquefaction involves ONLY saturated sand !
It is loose of strength due to overpressure problems



NTC 2018

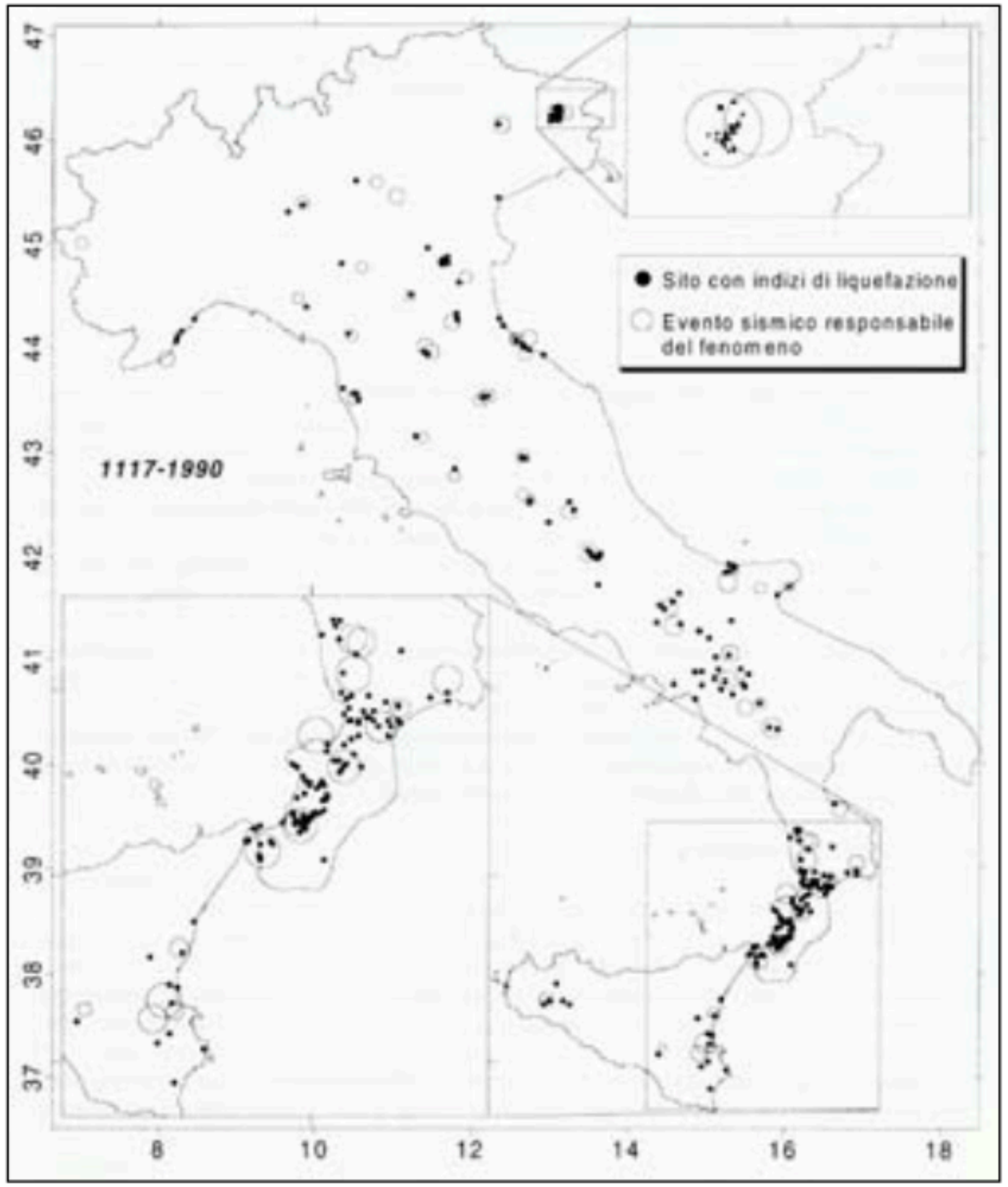
(N1)60 < 30 or qc1N < 180
N1 60 = (Standard Penetration Test) normalised at effective tension of 100 kPa
qc1N (Cone Penetration Test) normalised at effective tension of 100 kPa

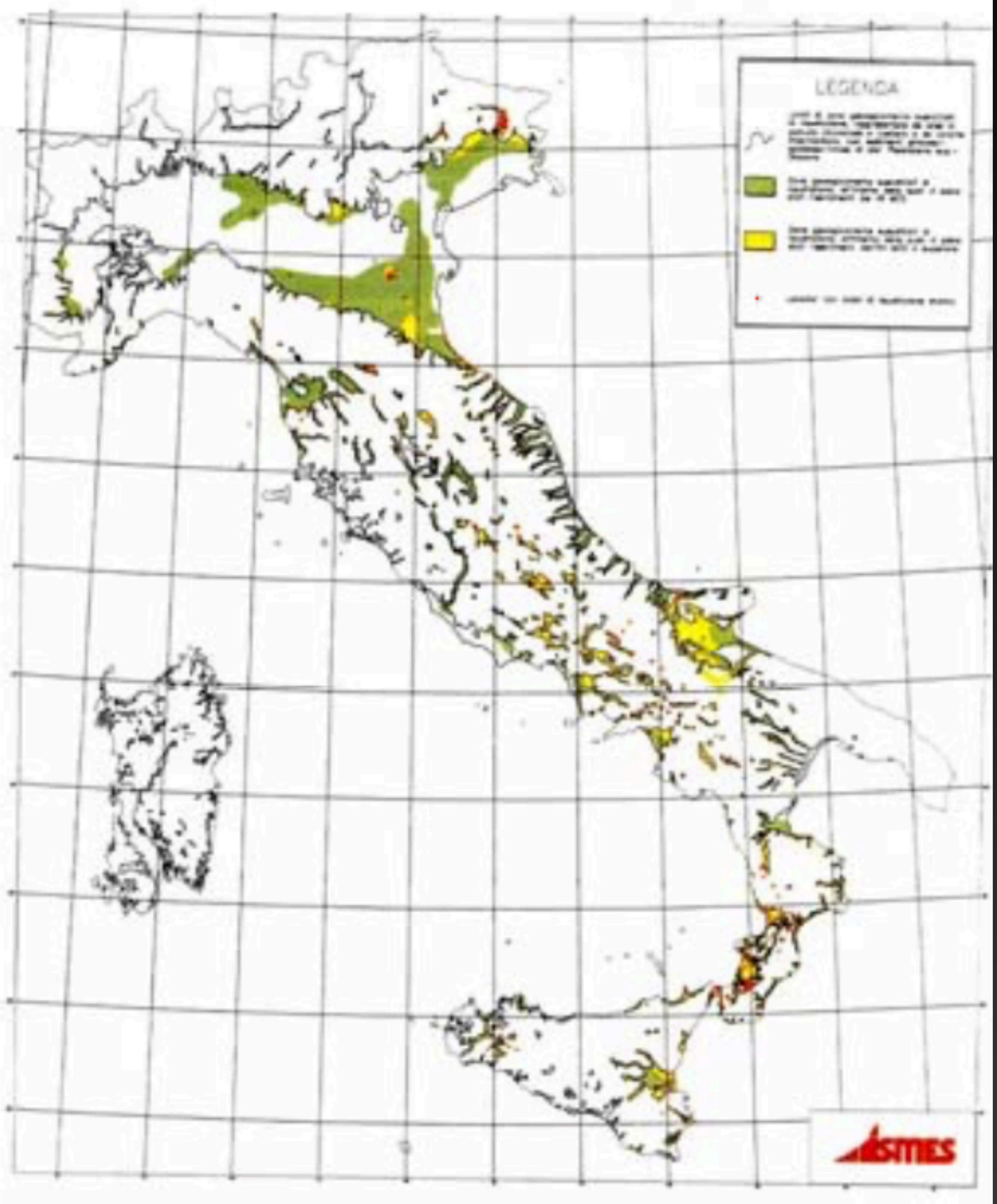
Essential condition:

- Saturated sand (with water table < 15m from the surface)
- Magnitude >5 (or > ≈ 0.1g)

Induced effect: Liquefaction

Liquefaction involves ONLY certain zones!





Examples: Cases in Italy

Induced effect: Liquefaction

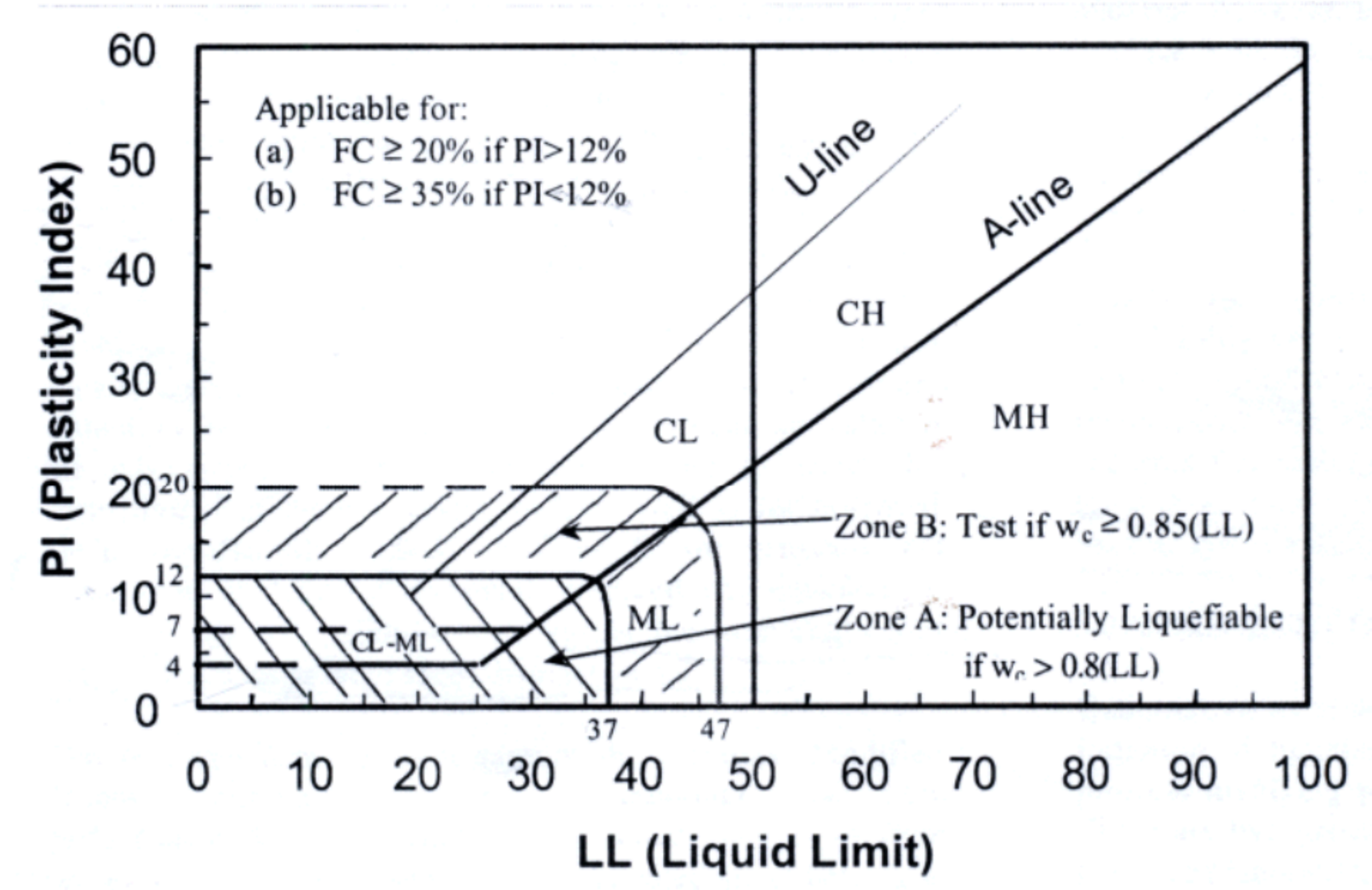
Liquefaction involves ONLY certain soils!

Geological criteria

Categoria	***Morfologia***	***Liquefazione***
A	*River beds, swamp, marsh, reclaimed land*	*Probable*
B	*Levee, flood plains, sandy beach, conoids*	*Possible*
C	*Terraces, hills, mountain*	*Not probable*

Composition soil criteria

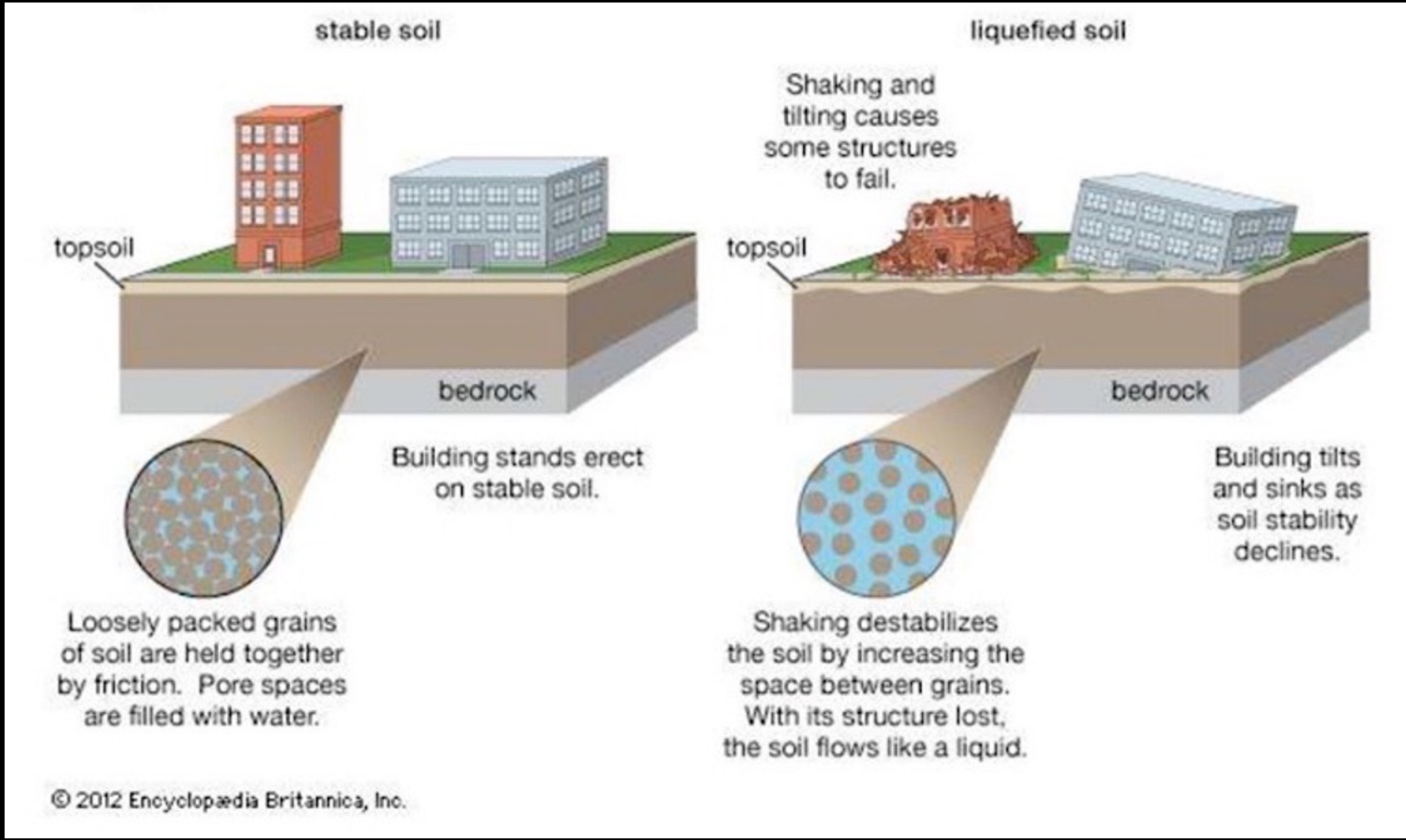
(Literature lab test)



Induced effect: Liquefaction

Liquefaction involves ONLY saturated sand !

It is loose of strength due to overpressure problems



Induced effect: Liquefaction

A shear strength problem

In case of seismic event
We can observe a decrease of the soil shear strength

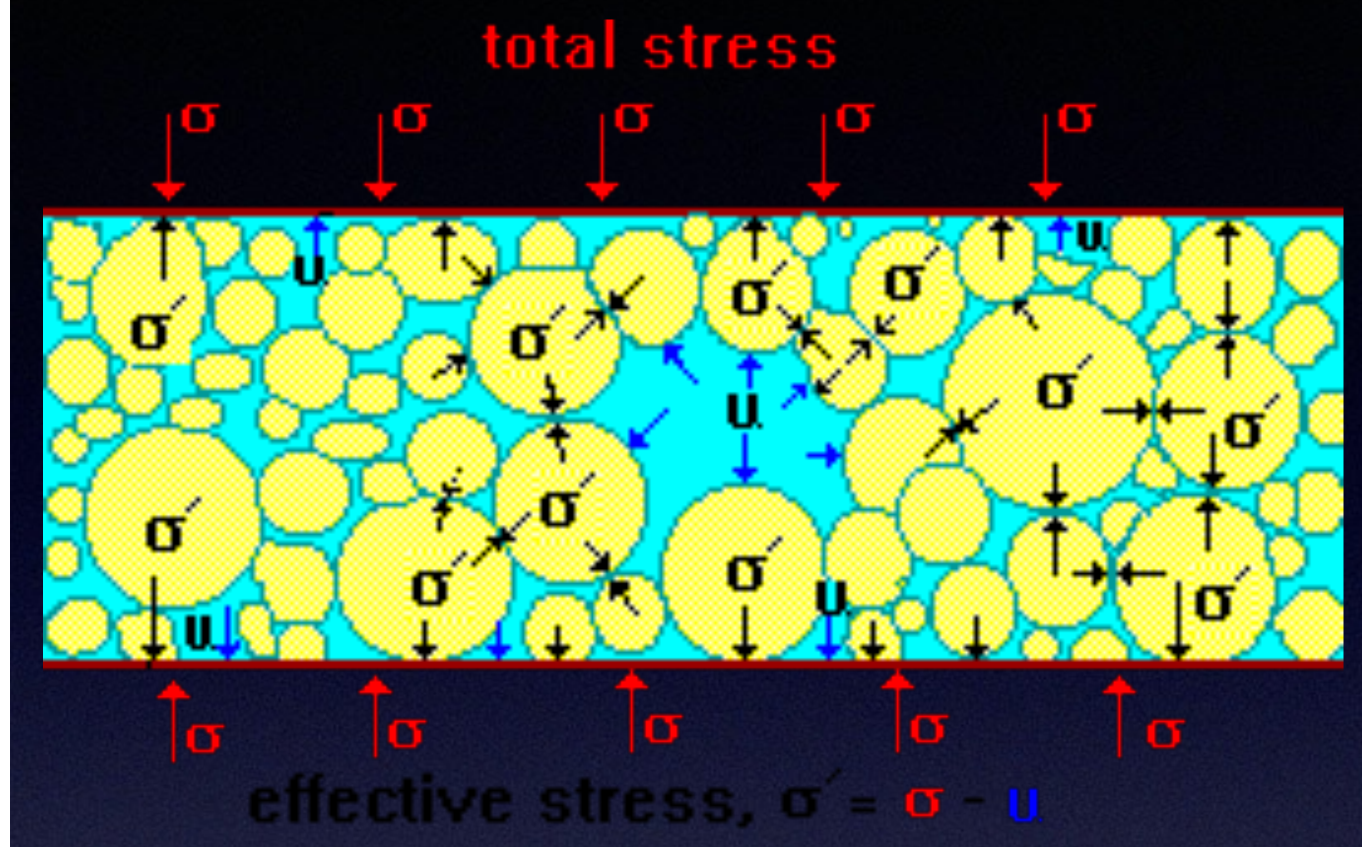
- Increase of interstitial pressure (Δu)
- Decrease of resistance parameters (c', ϕ', c_u)

App. cohesion *Vertical Pressure* *Neutral pressure* *Friction angle*

$$\tau_f = c' + (\sigma - u)\tan\varphi' \equiv c' + (\sigma_0' - \Delta u)\tan\varphi'$$

$$\tau_f = c_u$$

Shear strength



Total tension

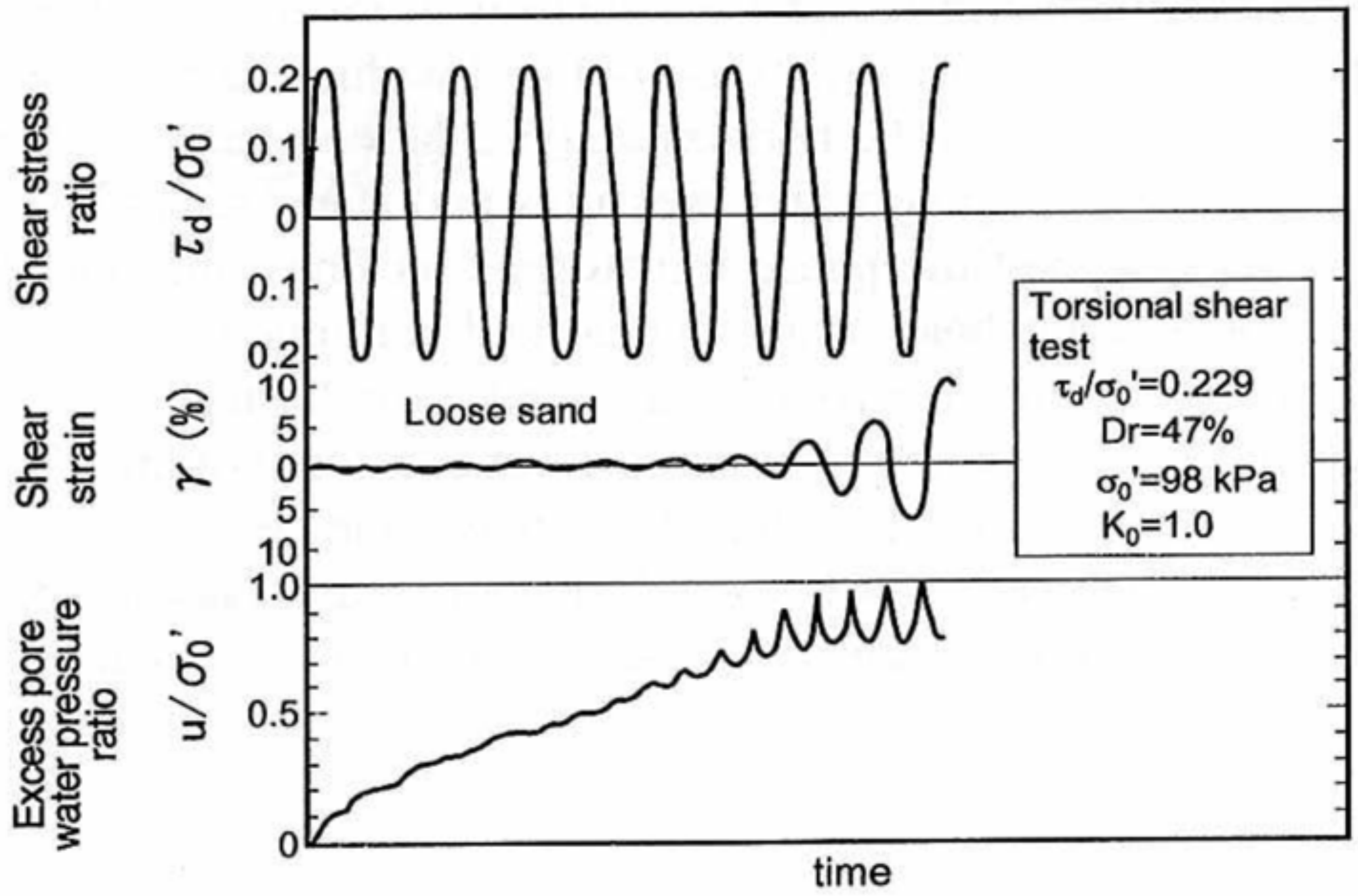
$$\sigma = \sigma' + u$$

Effective grain tension

Neutral fluid tension

Induced effect: Liquefaction

Saturated sand over cyclic load



Christchurch, NZ

(Ishihara, 1985)

- Increase of shear stress due to earthquake motion
- Quick Increase if interstitial pressure

Liquefaction conditions

$$\tau_f = c' + (\sigma_0' - \Delta u) \tan \varphi' \rightarrow 0$$

$$\frac{\Delta u}{\sigma'_0} \rightarrow 1$$

Loose of shear strength !

Loose of load Resistance

Induced effect: Liquefaction

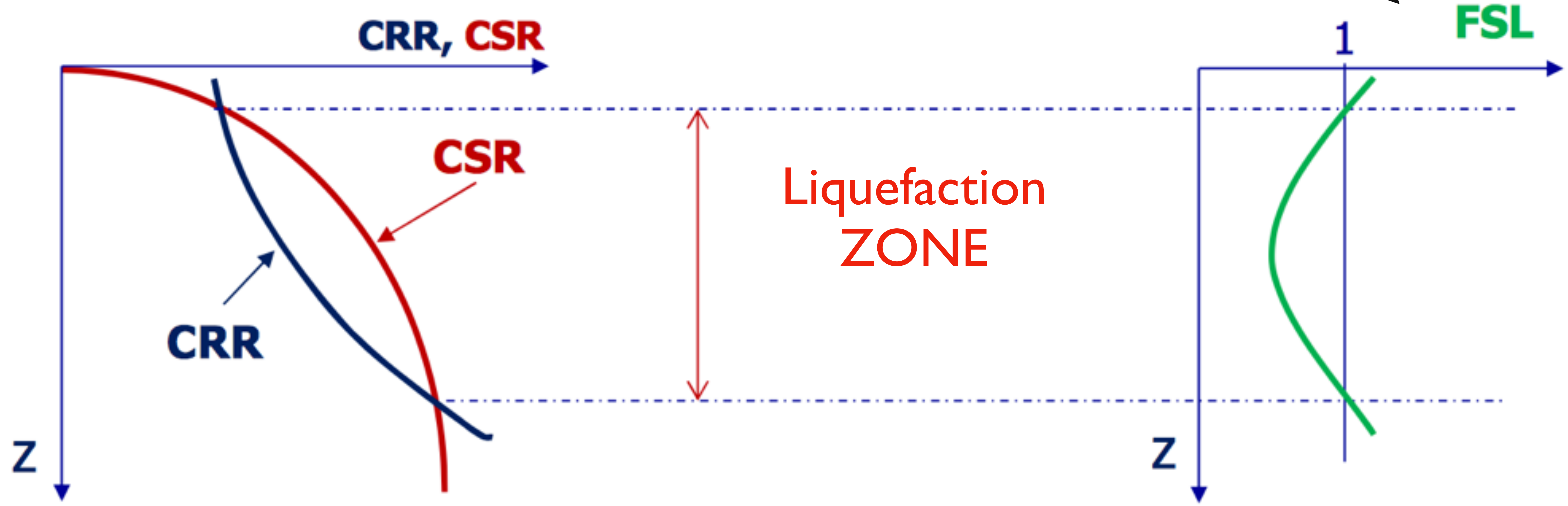
Simplified model for liquefaction

Determine the safety factor for liquefaction FSL defined as the ratio between applied force and resistance:

FSL = CRR/CSR

FSL<1 Liquefaction !

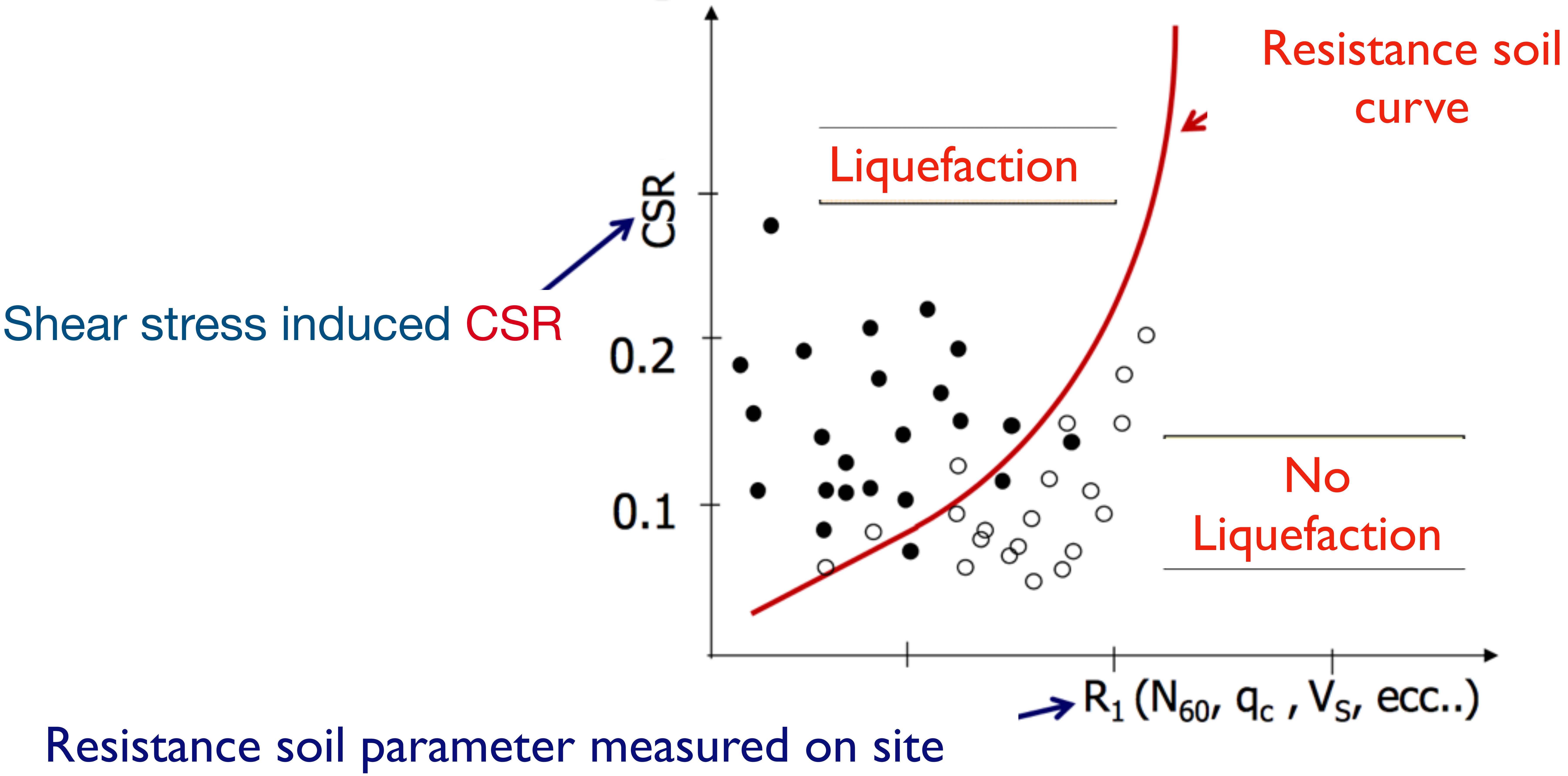
- CSR = shear stress induced by the earthquake (at a given depth, i.e. pressure condition)
- CRR = cyclic shear resistance of the soil (at a given depth, i.e. pressure condition)



Induced effect: Liquefaction

Simplified model for liquefaction as ABACUS

Abacus based on empirical observation of real cases



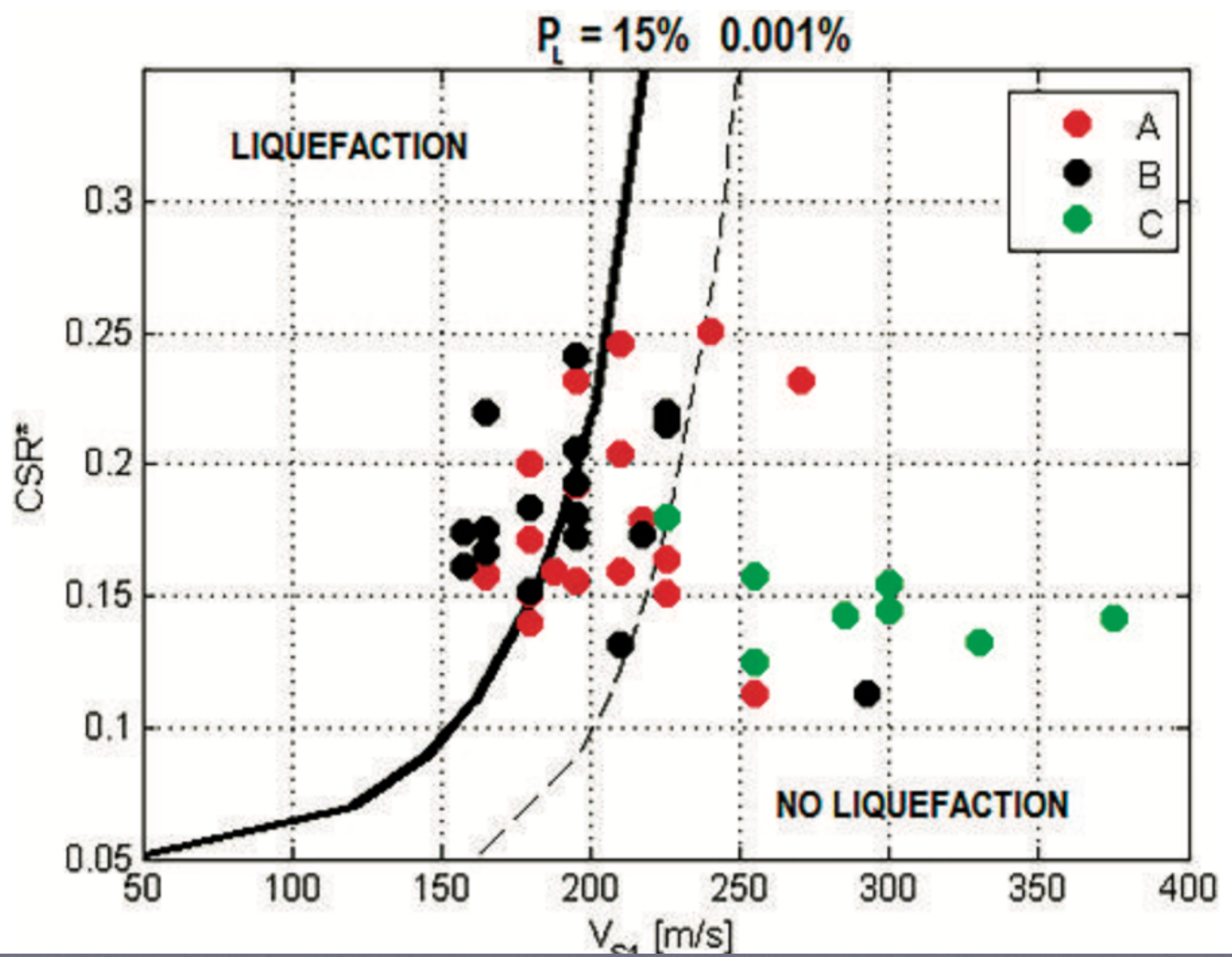
Induced effect: Liquefaction

CSR usually defined as in Seed & Idriss 1971:

$$CSR = \left(\frac{\tau_{eq}}{\sigma'_{v0}}\right) = 0.65 \cdot \left(\frac{a_{max}}{g}\right) \cdot \left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) \cdot r_d$$

a_{max}= Maximum surface acceleration
σ_{v0}= Total lithostatic pressure
σ'_{v0}=Effective lithostatic pressure
r_d= Depth normalised factor

CRR from on site geochemical or geophysical soil strength measurements

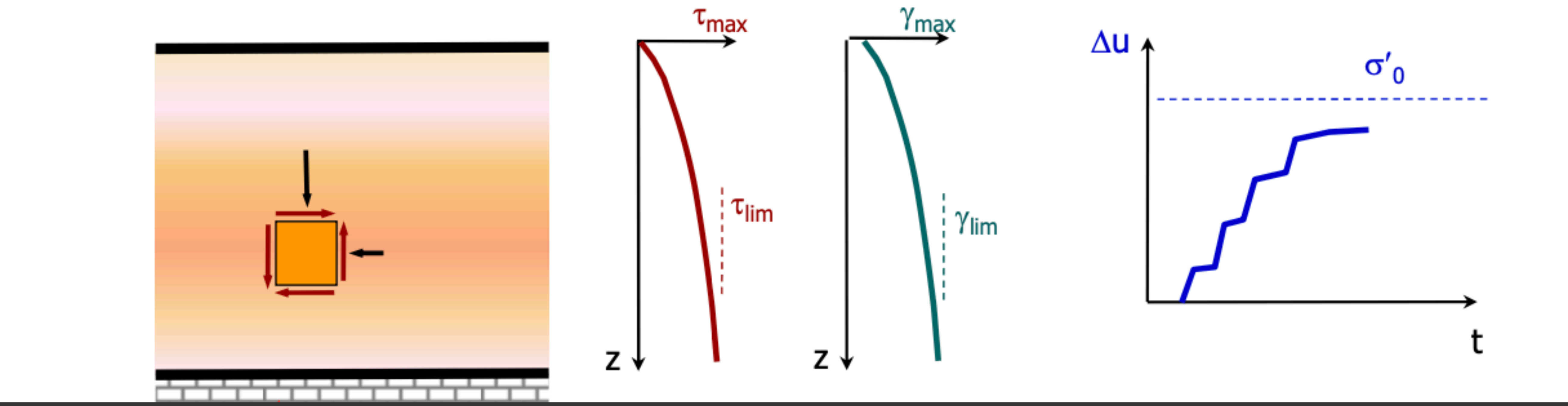


Induced effect: Liquefaction

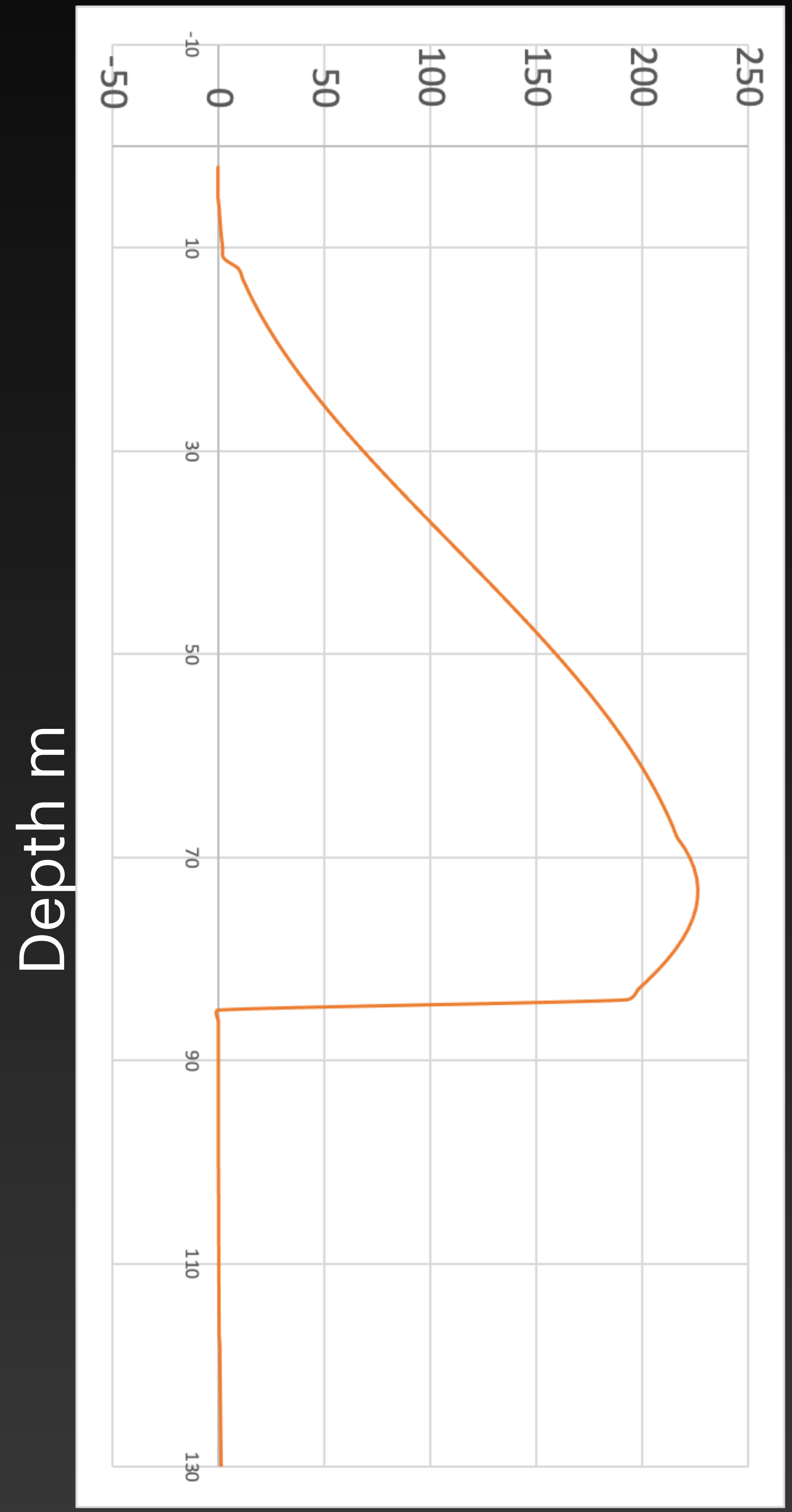
Advanced methods: based on Seismic Response Analysis

Synthetic stress load induced on the soil at the several depth of the soil column

With computational solution of motion



Motion parameter

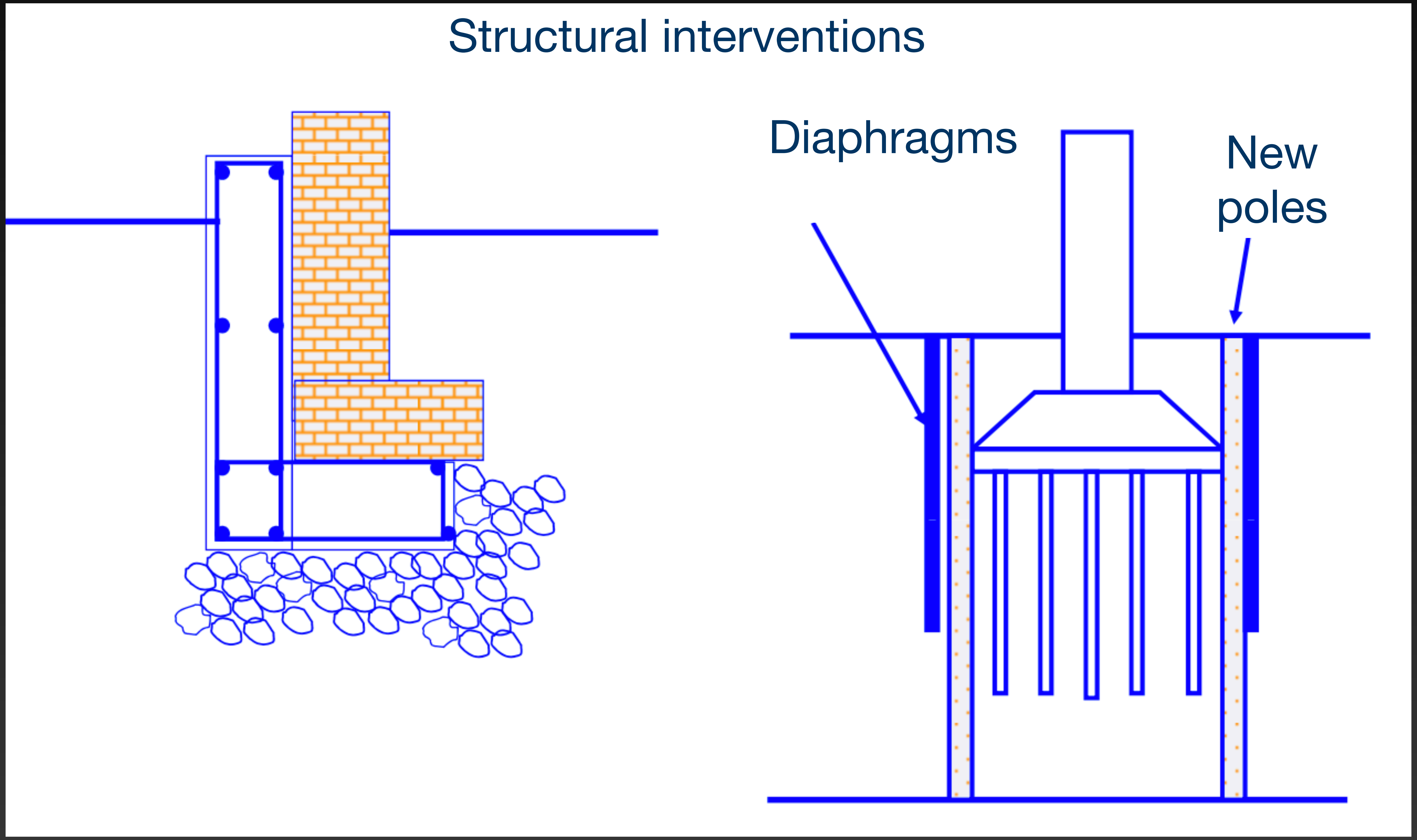


Induced effect: Liquefaction

Induced effect: Liquefaction

Mitigation criteria:

- Improve resistance strength (e.g. new pole foundation)
- Limit neutral overpressure (e.g. diaphragms)



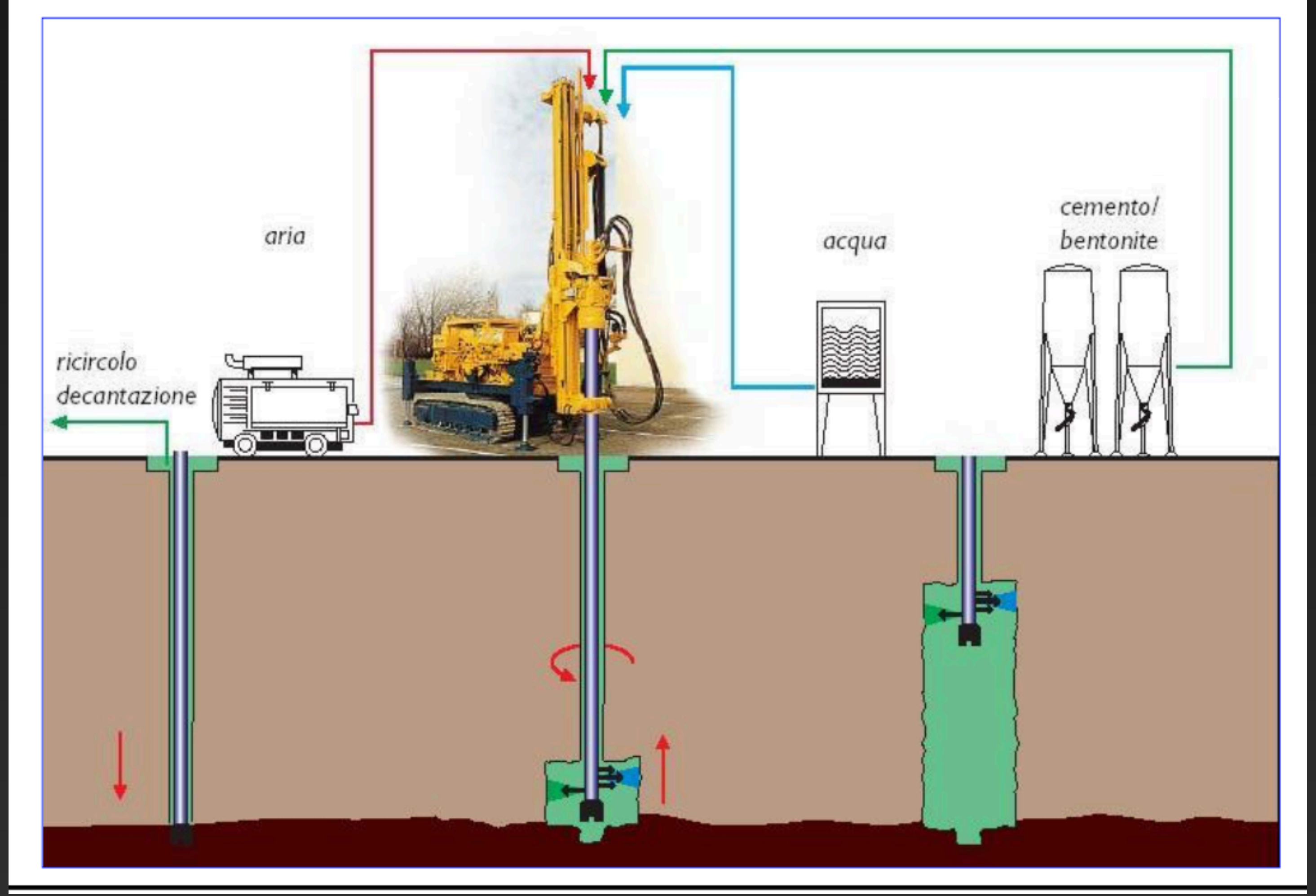
And many others technical solutions…

Induced effect: Liquefaction

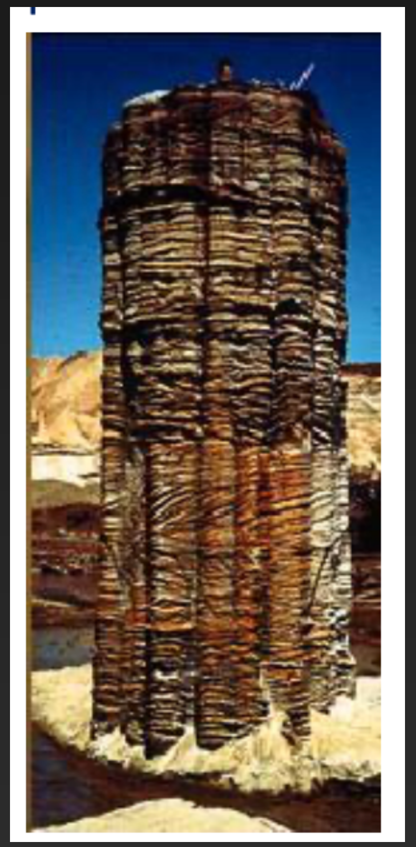
Improve resistance soil strength

e.g. >> density

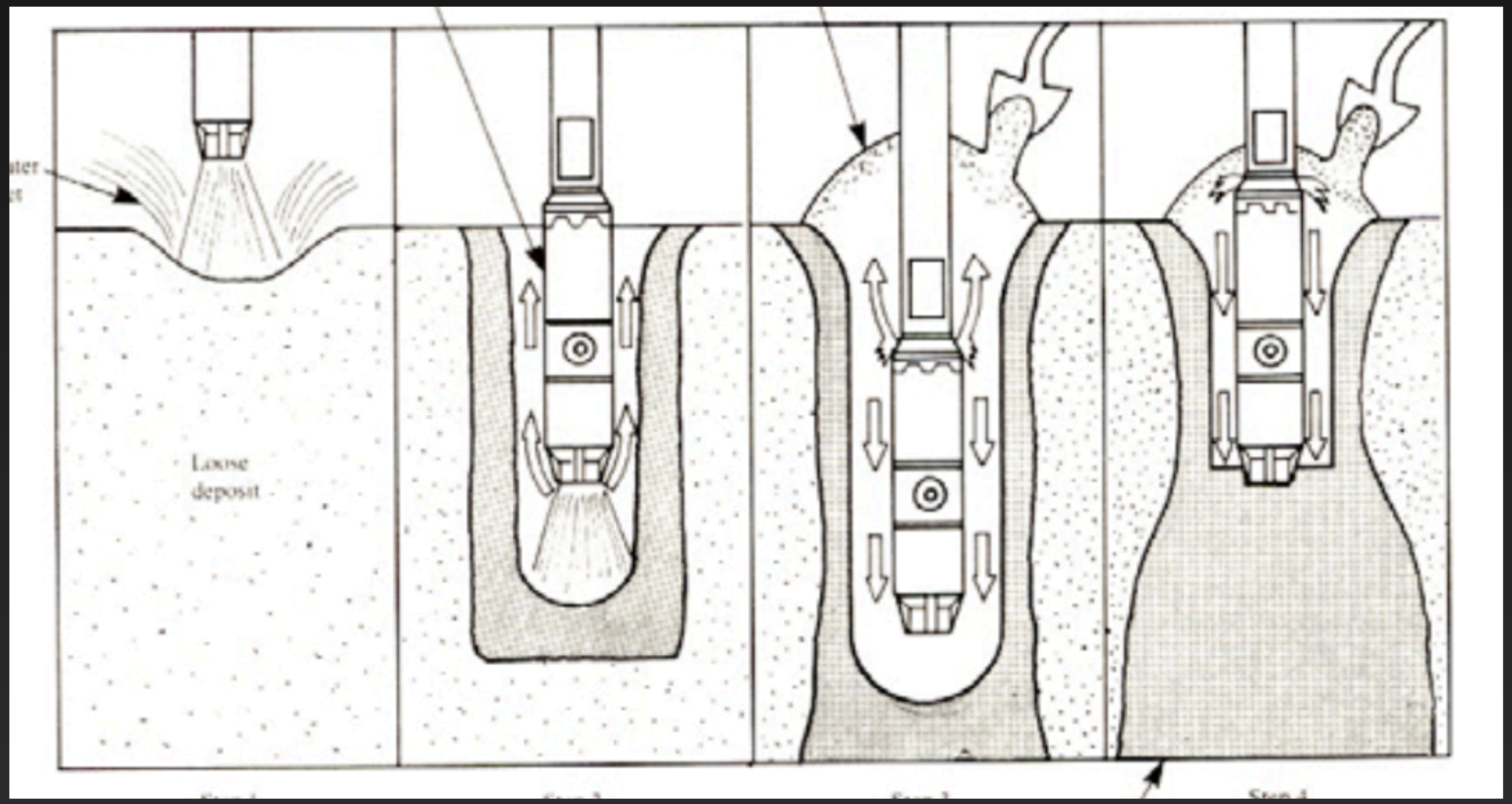
Jet grouting



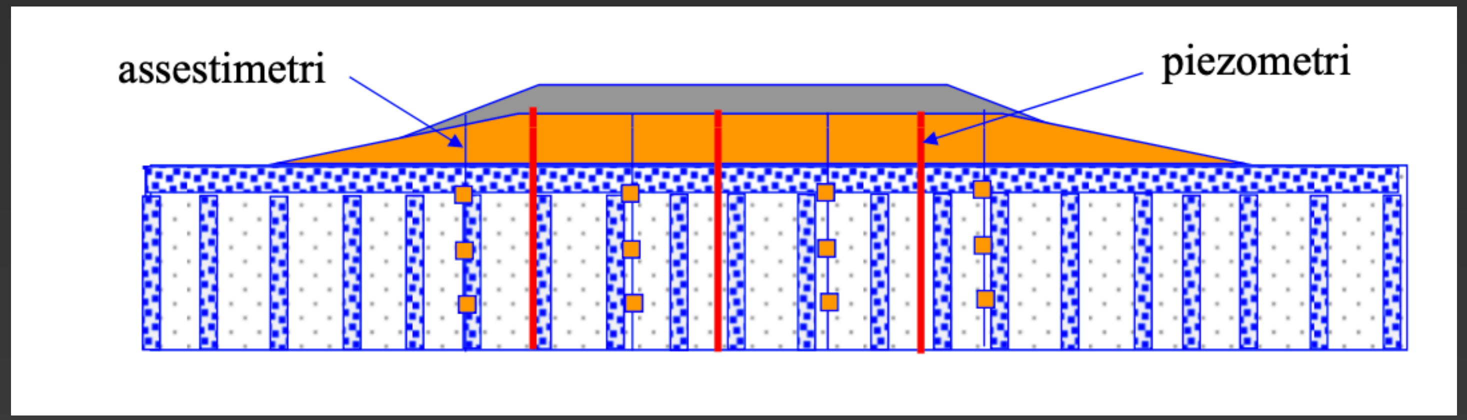
Heavy tamping



Vibro-floating



Over loads methods



Case histories 2D SRL

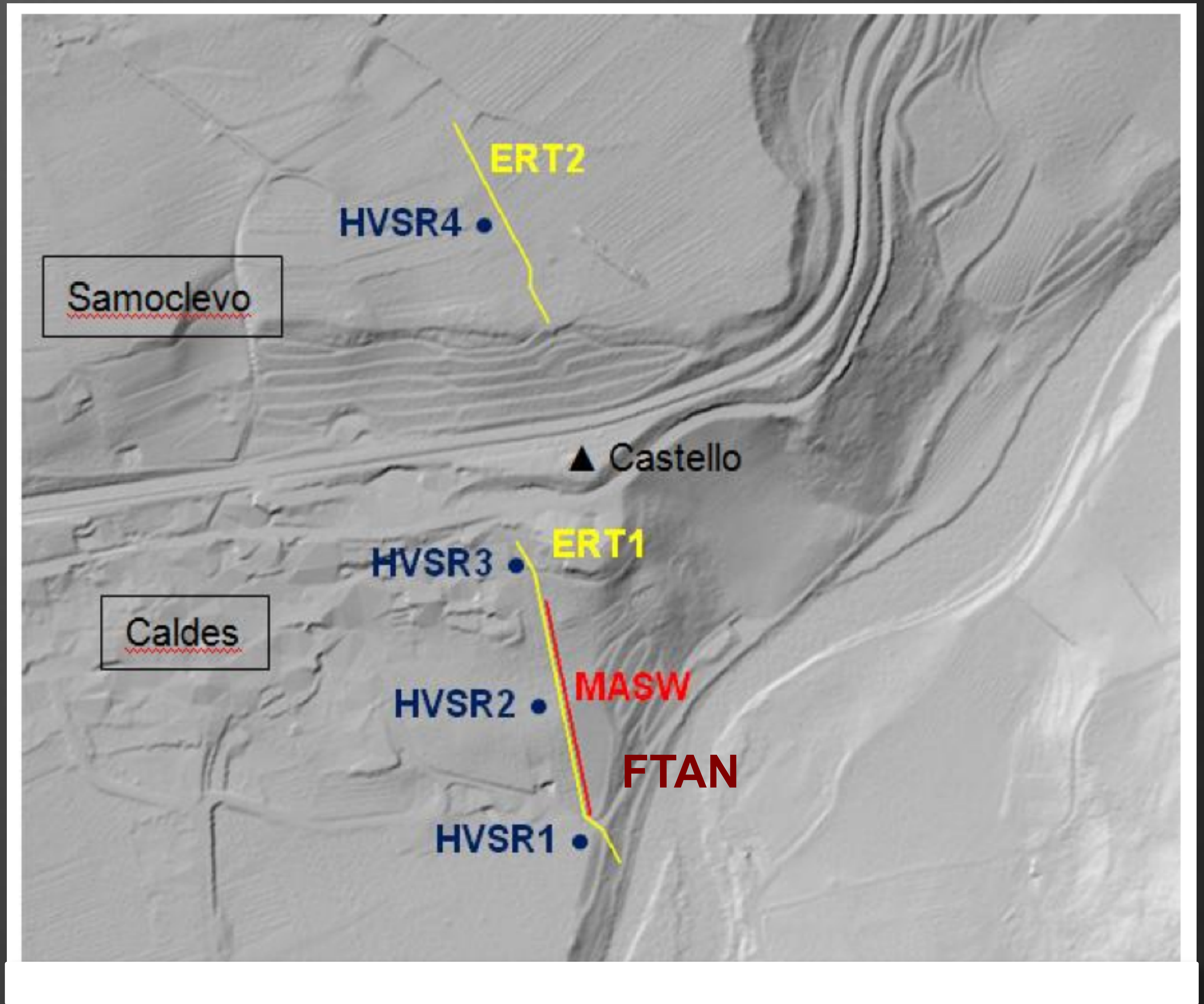
Indagini geofisiche

Indagini elettriche ERT

Indagini sismiche MASW

Indagini sismiche FTAN

Indagini sismica passiva HVSR



FTAN: 100m length, 1s rec.

MASW: 48 canali – spacing 3m – L. 144m

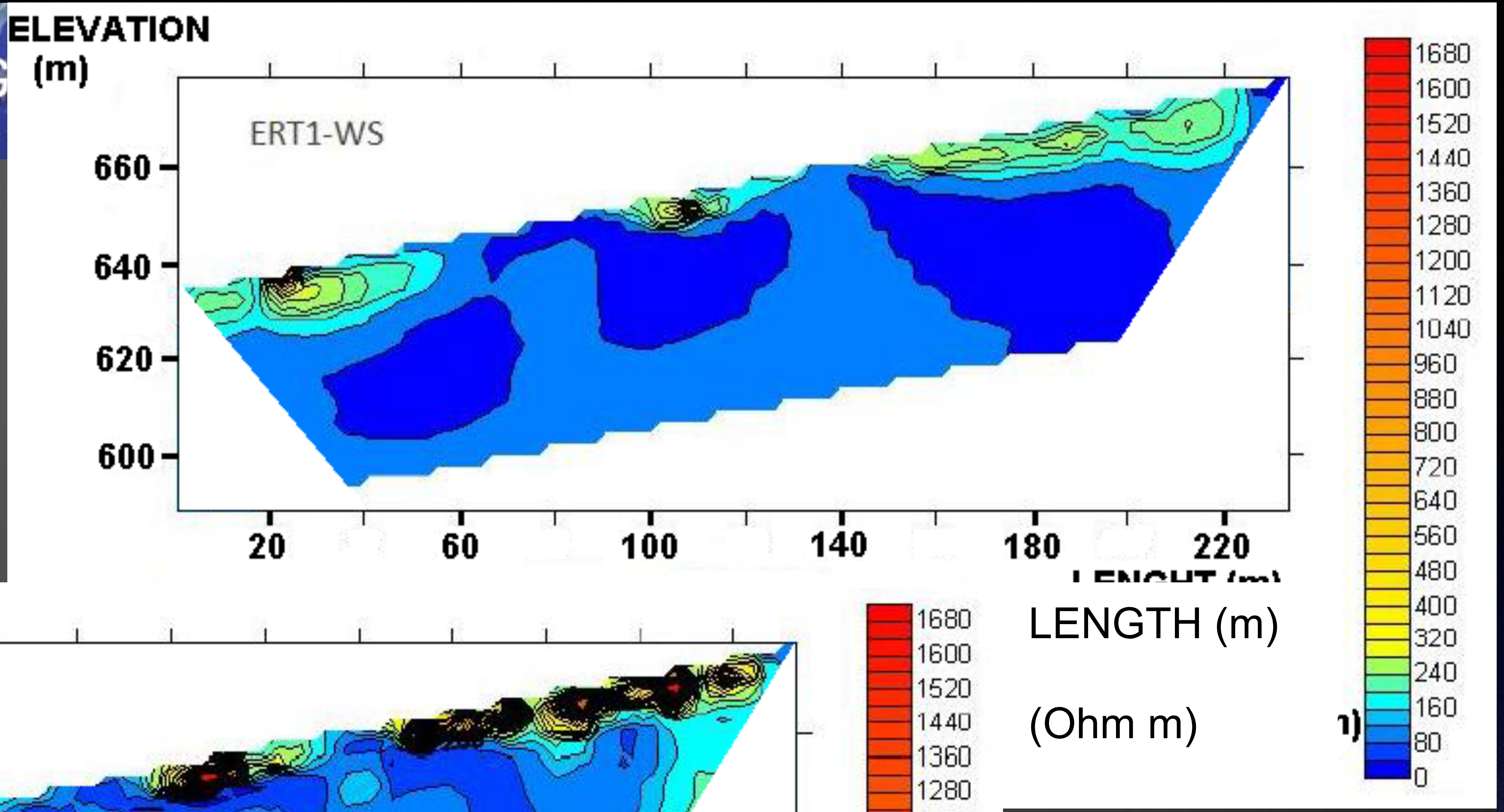
ERT 1: 48 canali – spacing 5m – L. 235m – config. WS e DD

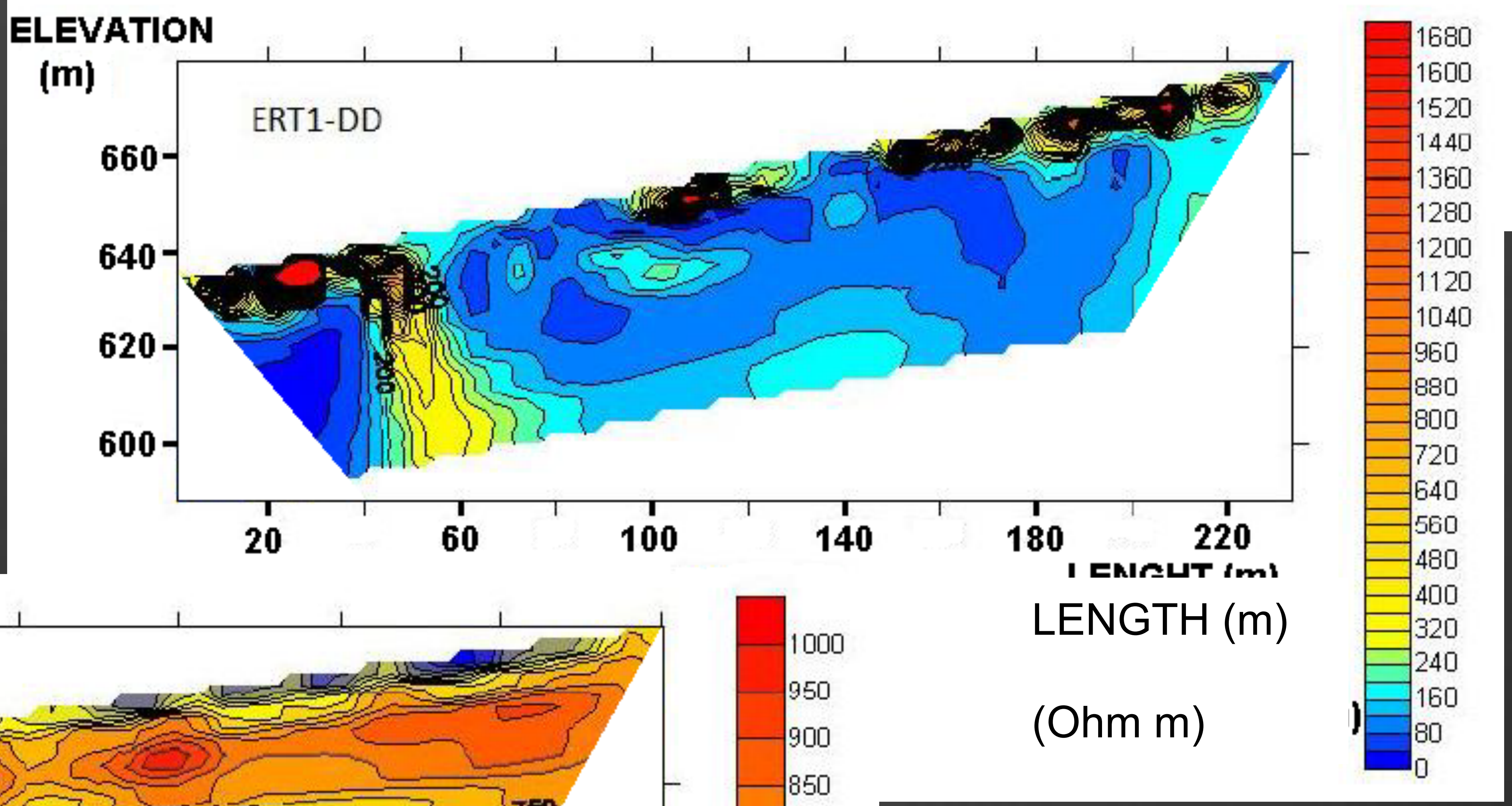
ERT 2: 48 canali – spacing 2m – L. 94m – config. DD

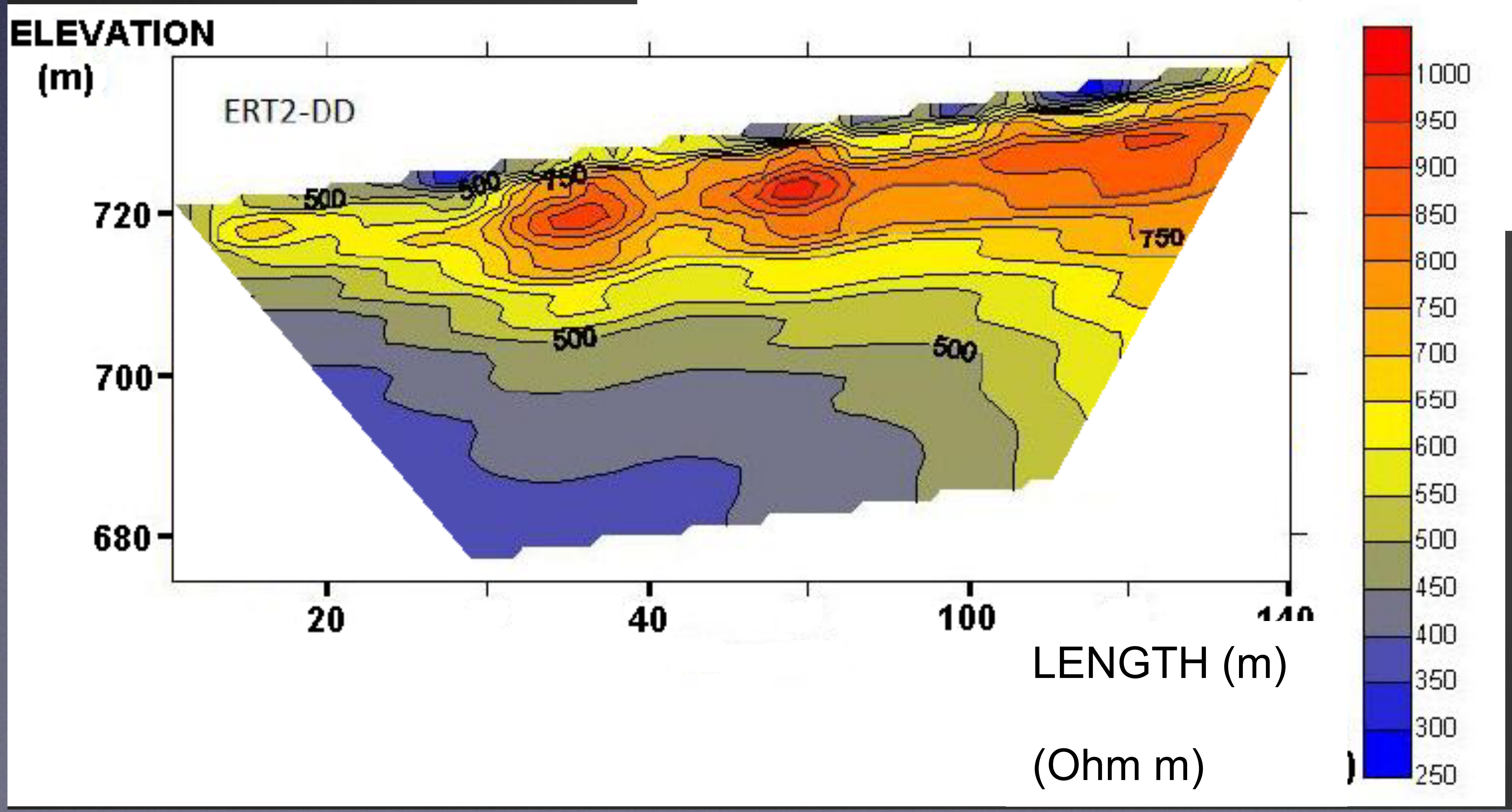
HVSR:: 4 prove – rec.time 20 min.

Indagini geofisiche

CASTEL CALDES
ERT1



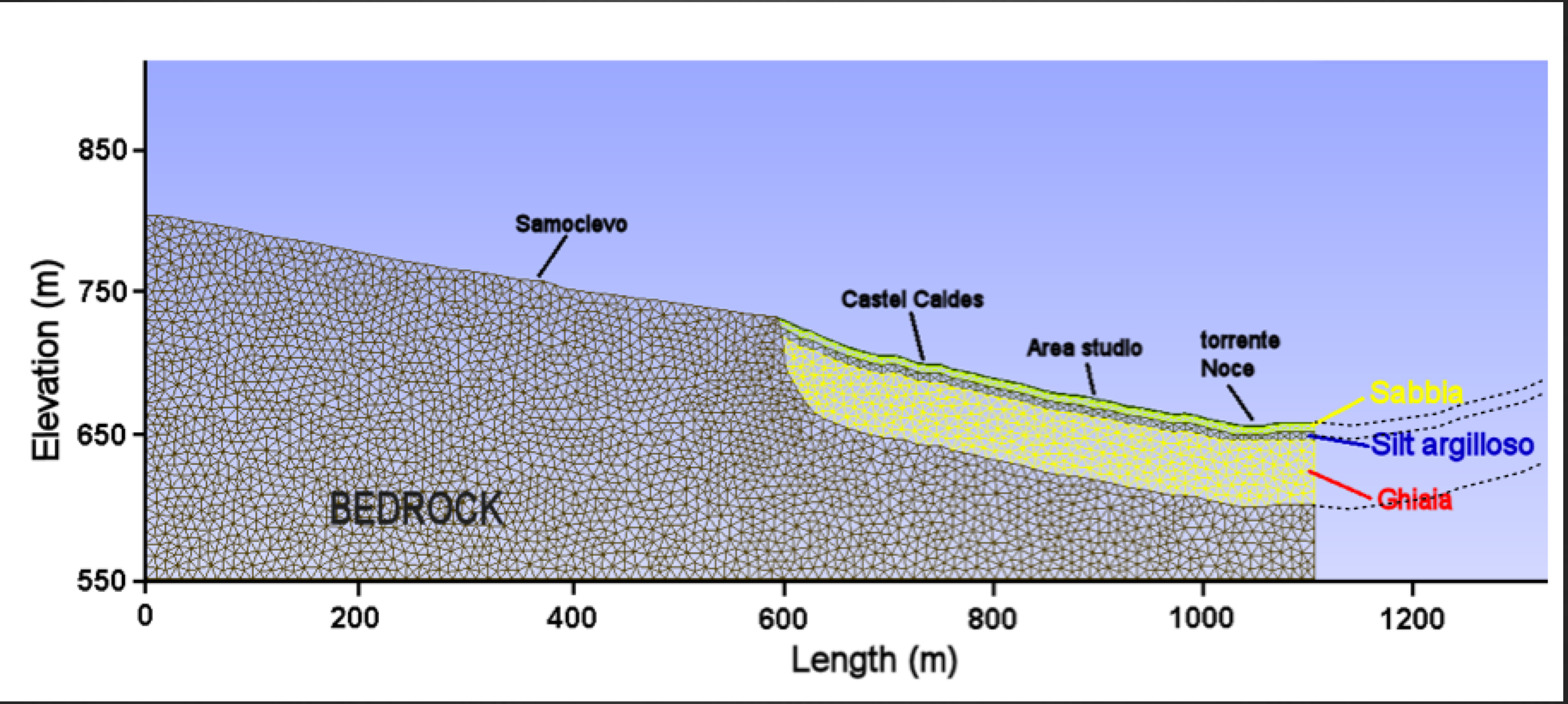




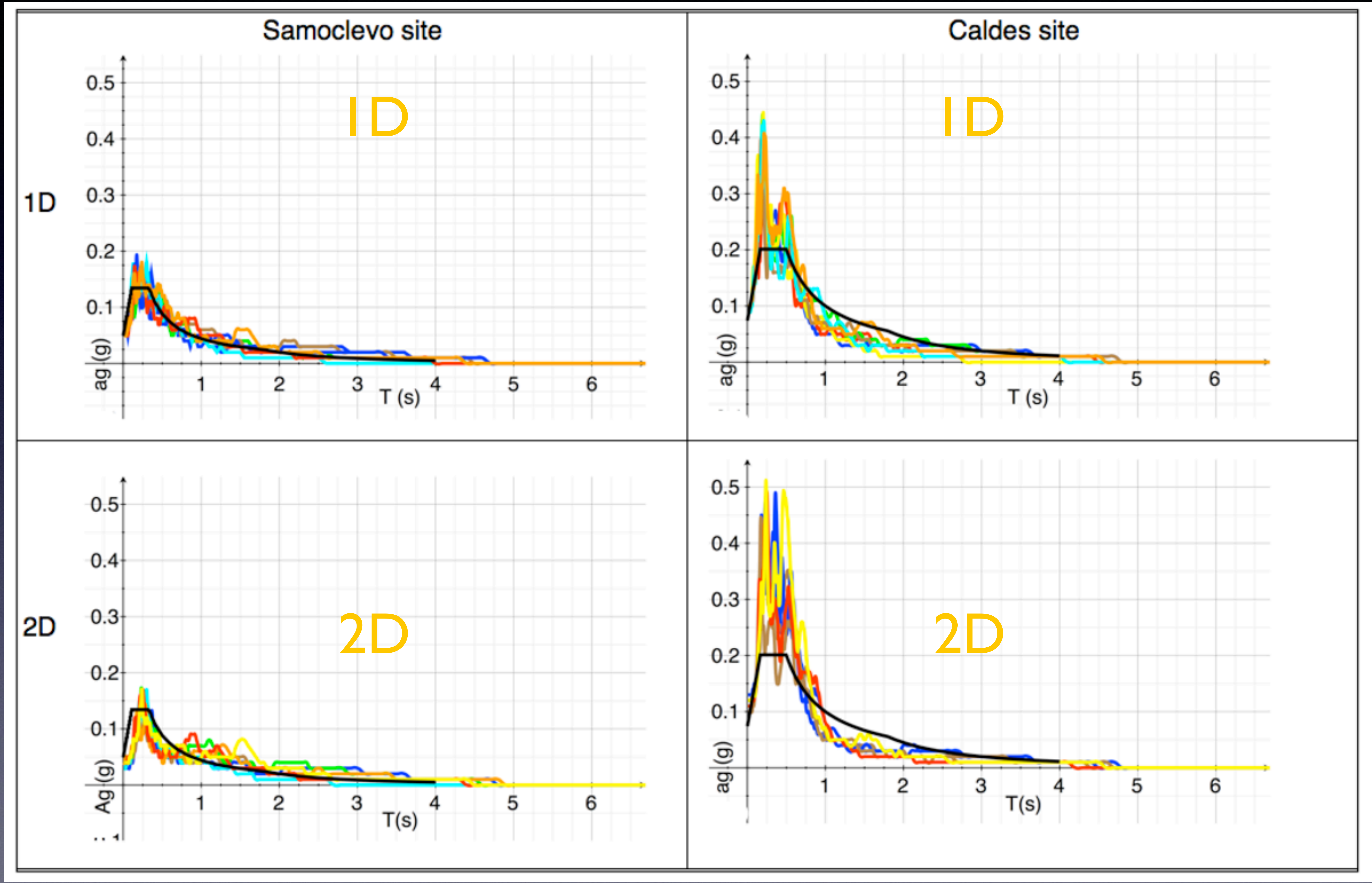
SAMOCLEVO
ERT2

- Risposta sismica locale

Modello di sottosuolo e mesh (elementi finiti) per la simulazione di scuotimento

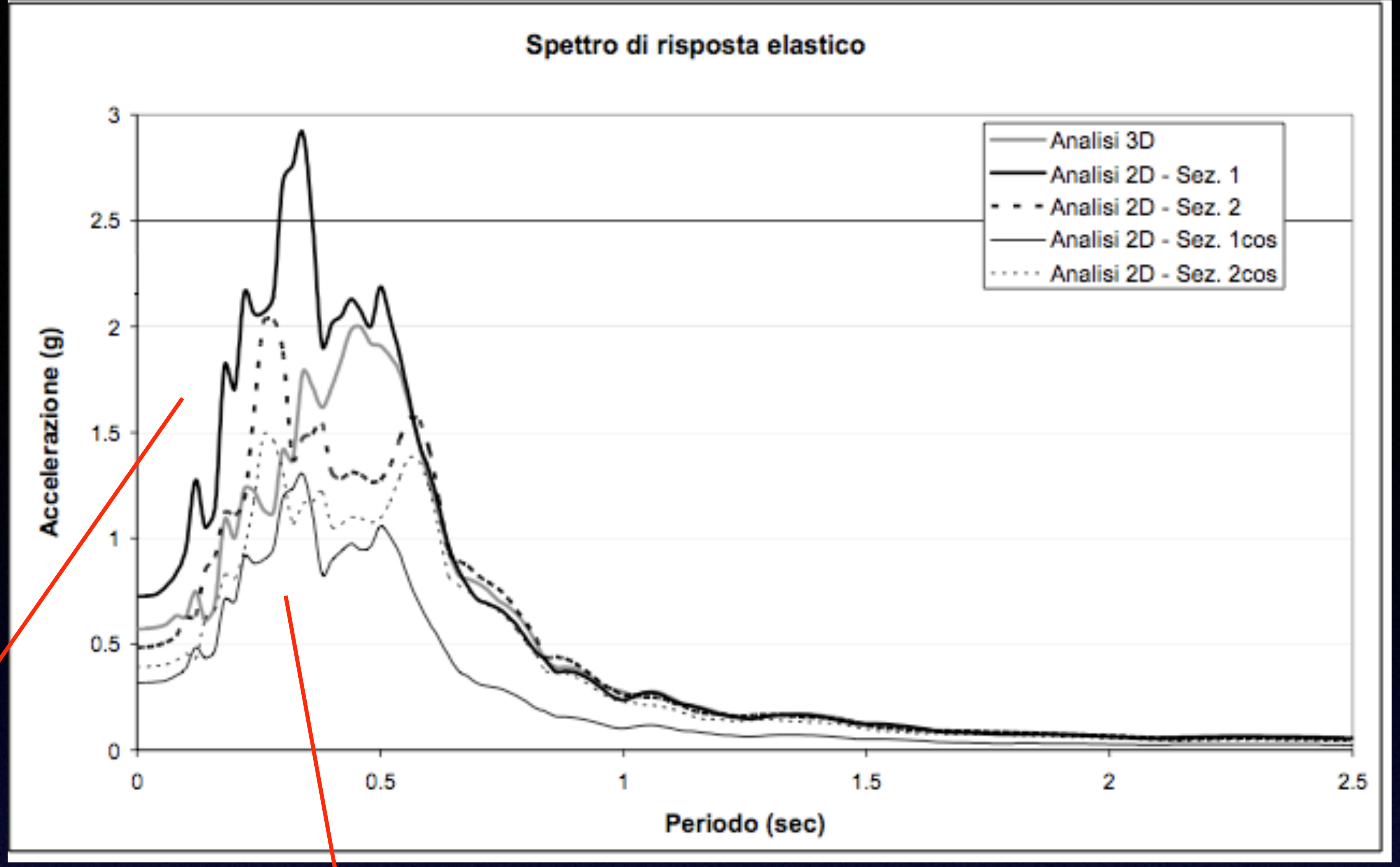


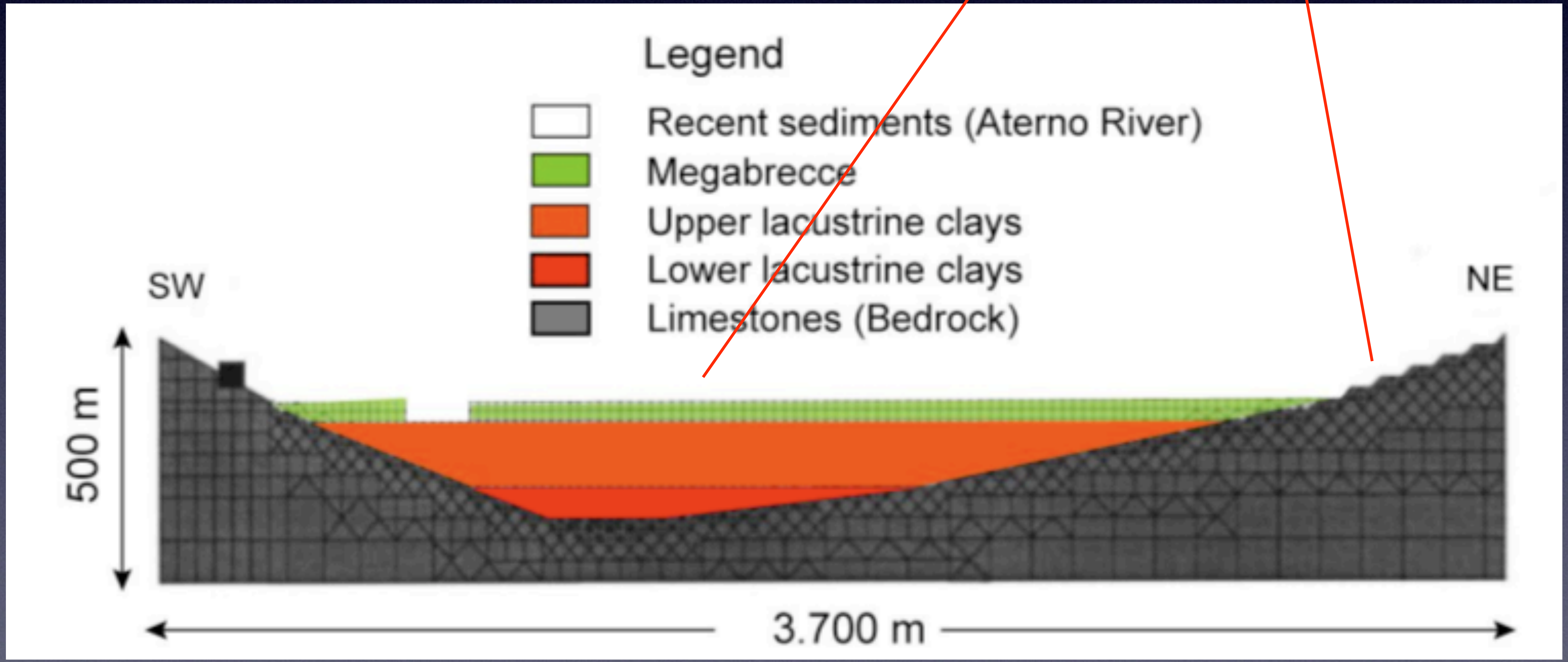
Boaga J 2016 Integrated geophysical-geological model for seismic local site response: the Caldes alpine slope case (Southern Alps, NE Italy)



Seismic local response is crucial

Local 2D effects

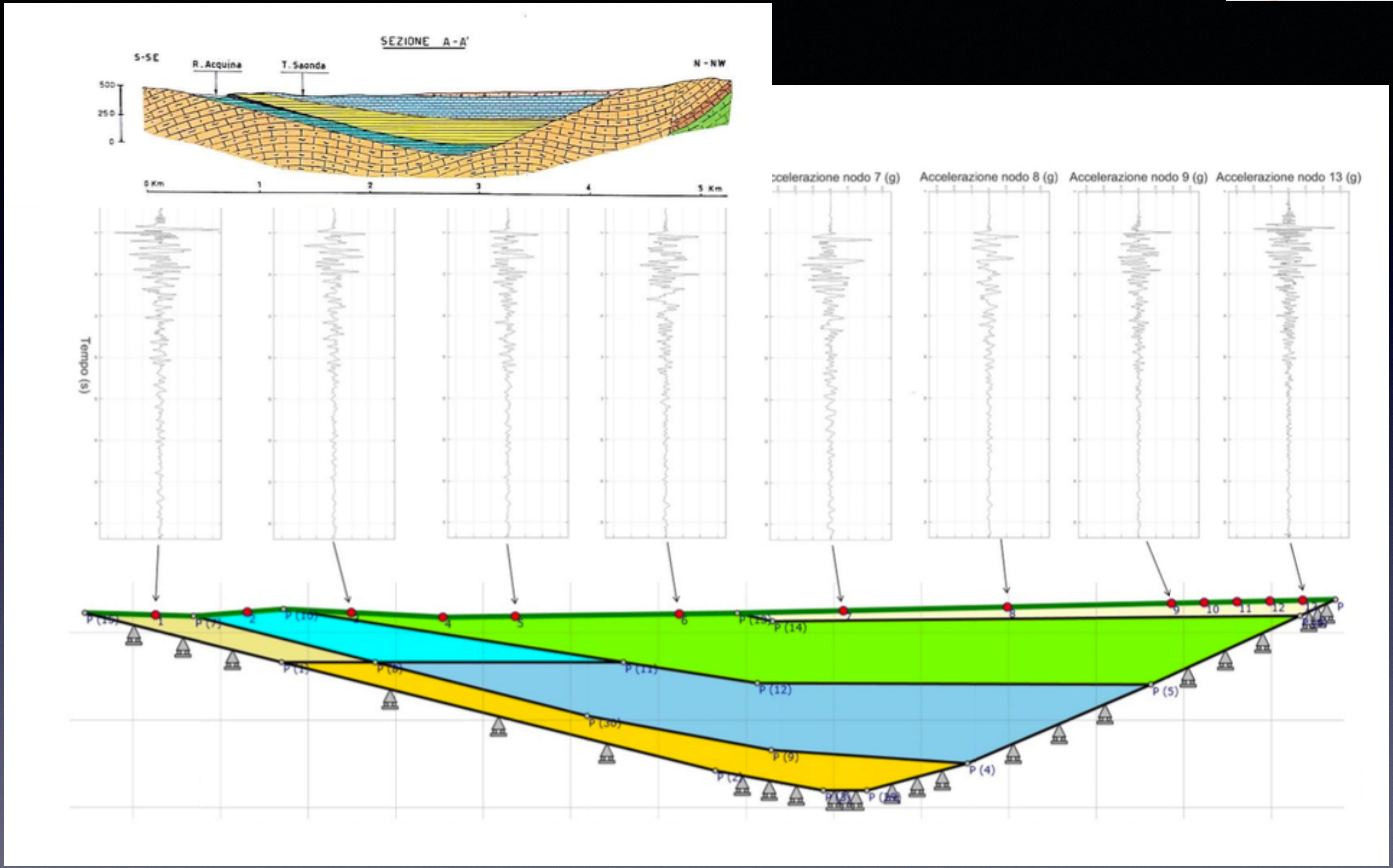




L'Aquila basin

Seismic local response

Gubbio basin



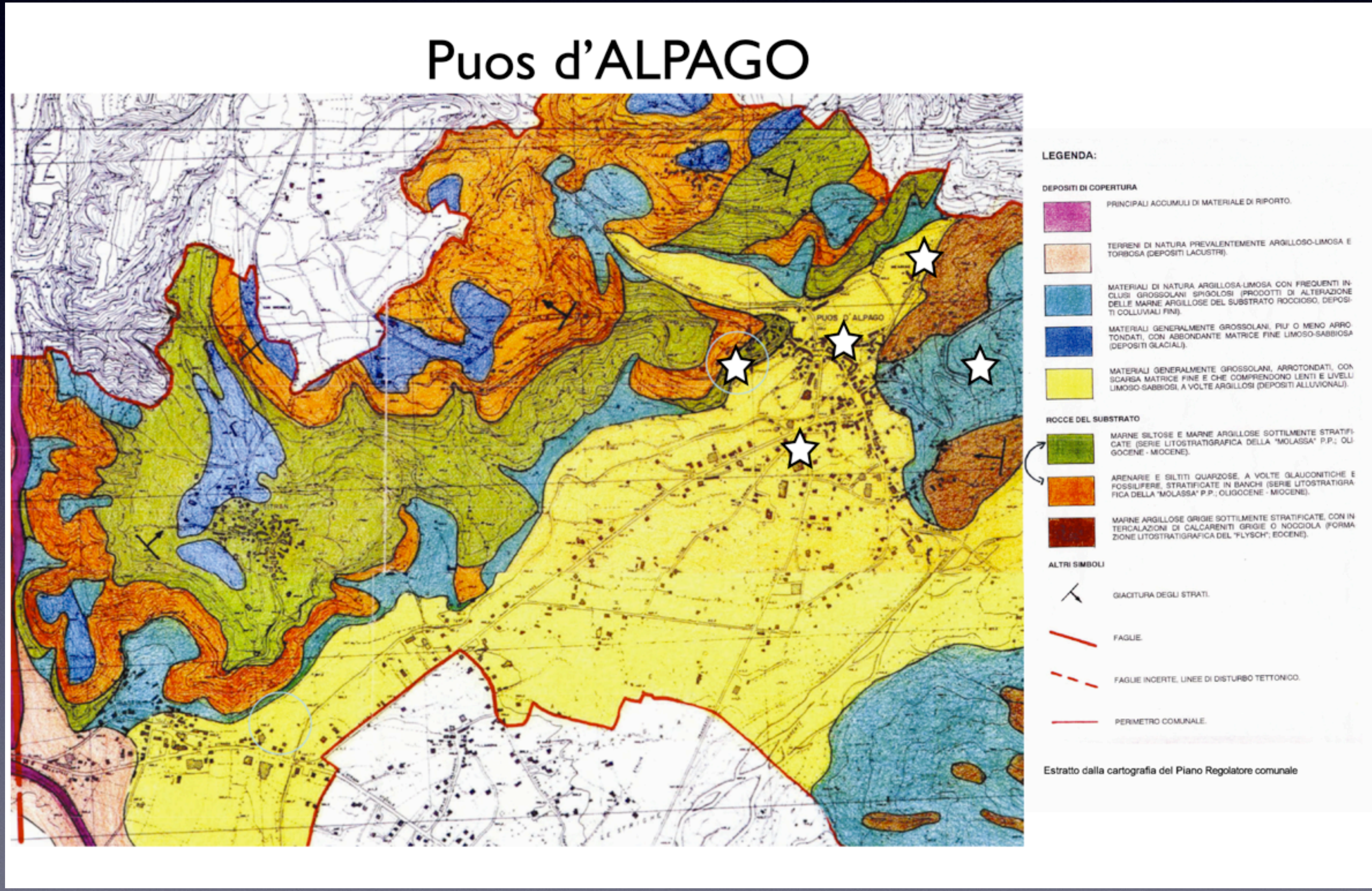
Seismic local response

Seismic Microzonation

Alpago

(Thesis: Ingegneria Ambiente Territorio 2013)

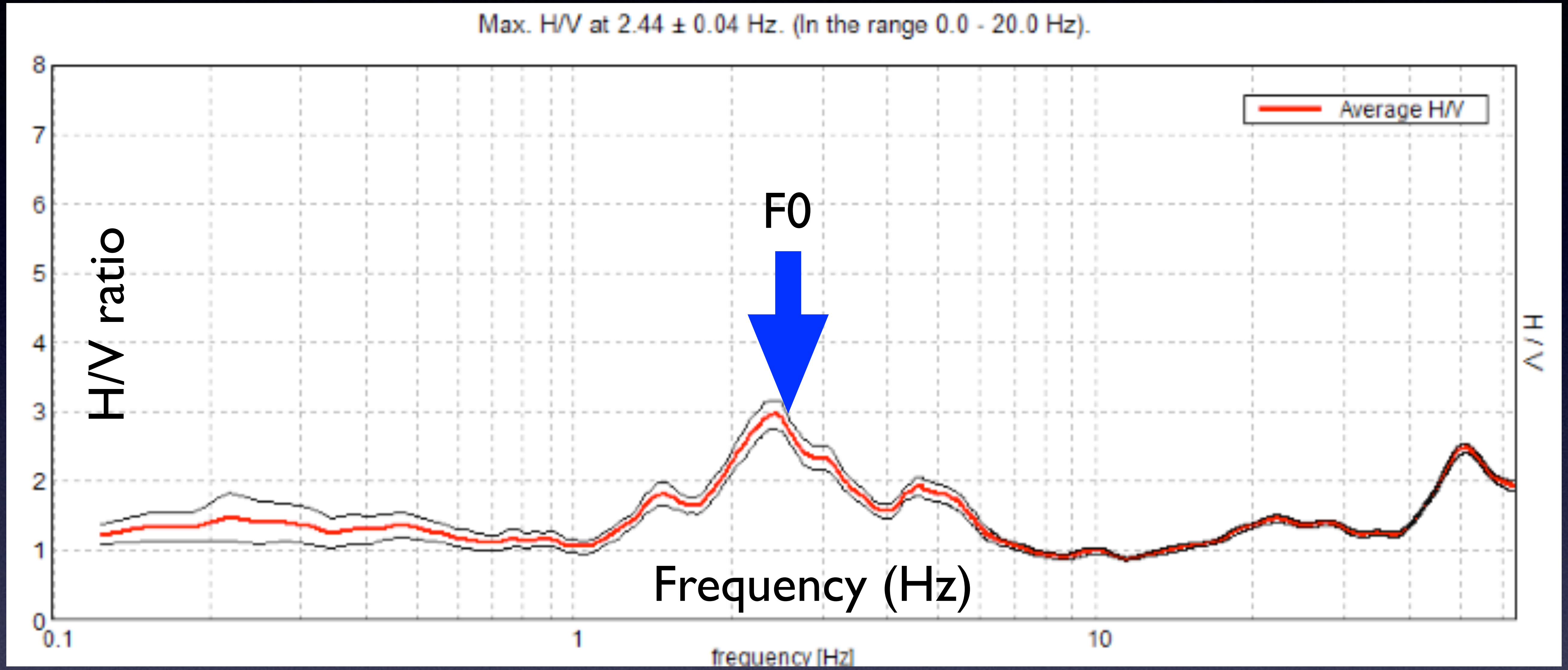
Level 1

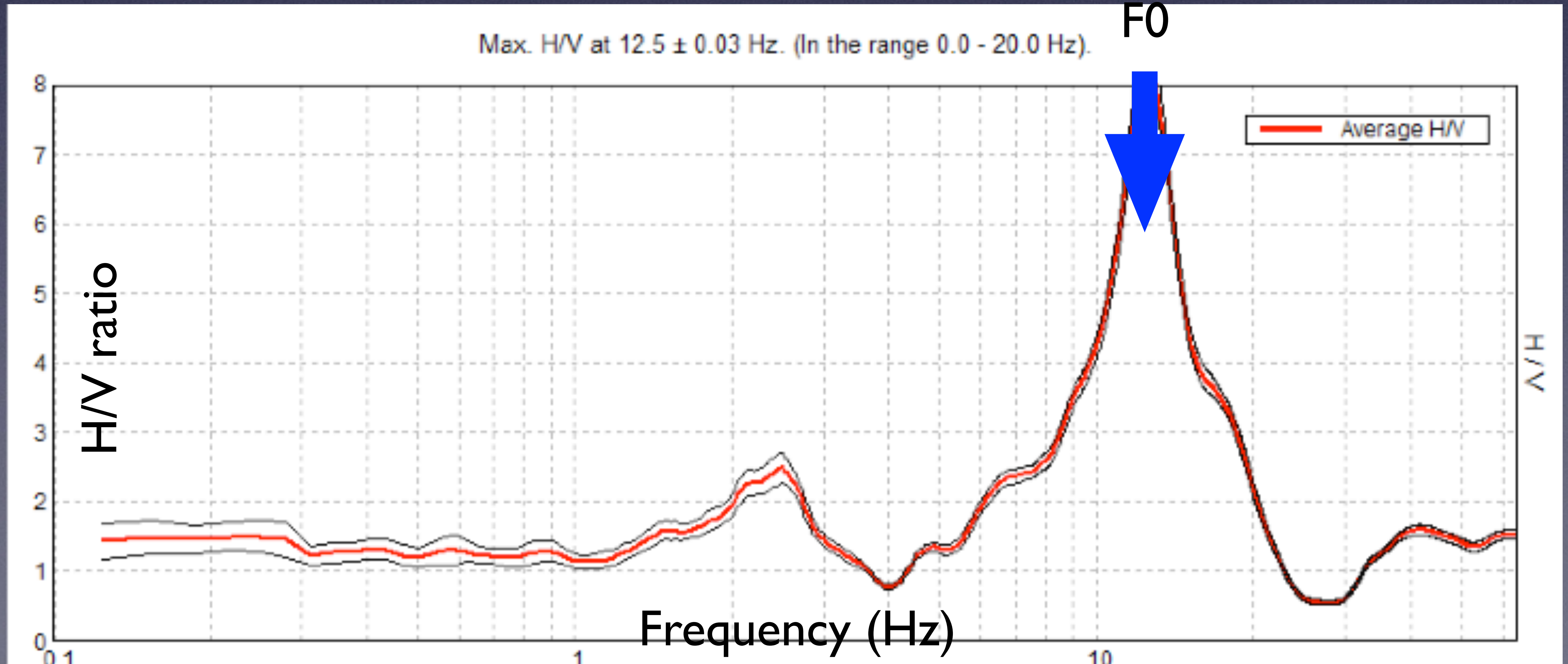


Seismic Microzonation

Resonance frequency of soil

Level 2

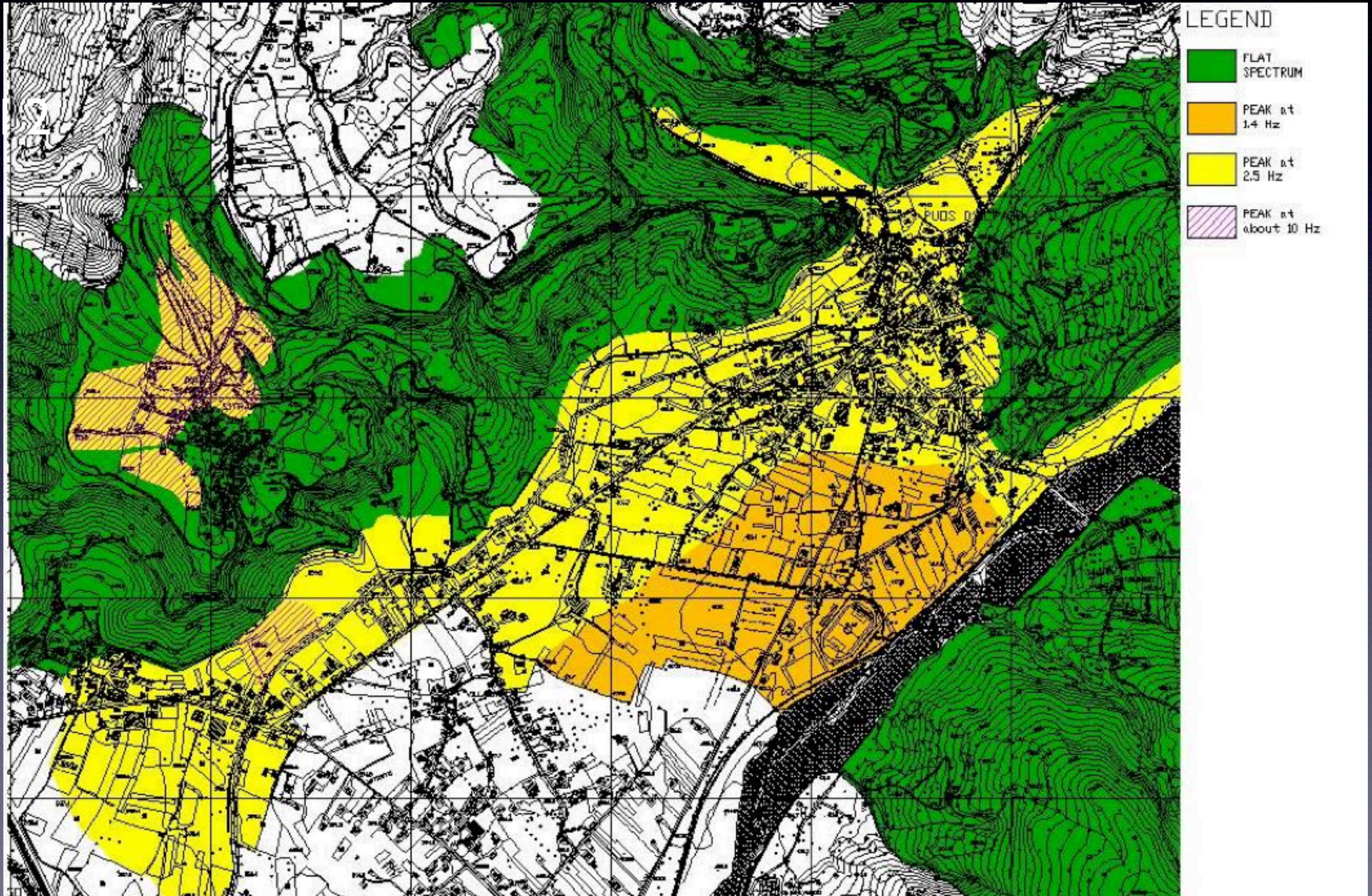




Seismic Microzonation

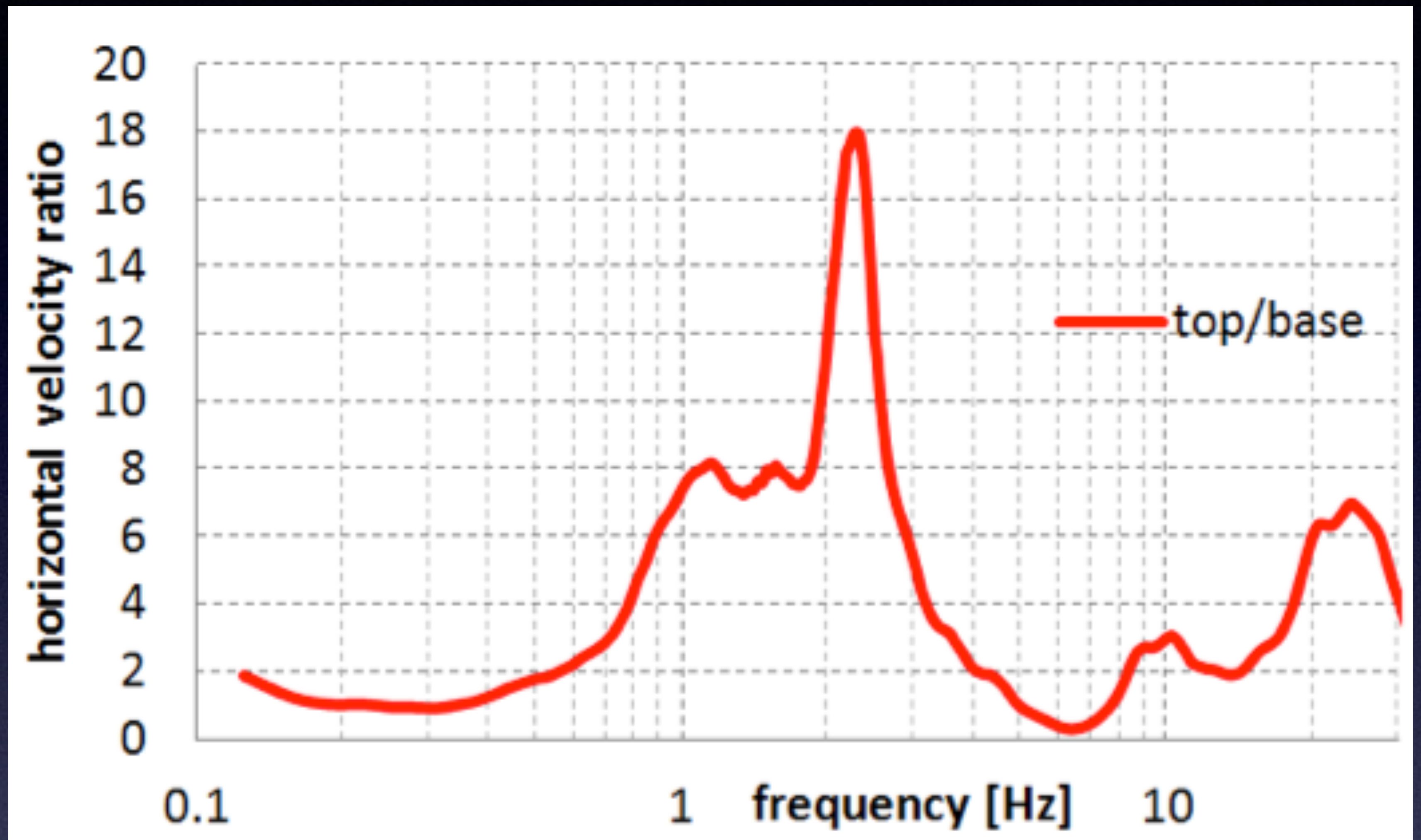
Level 2

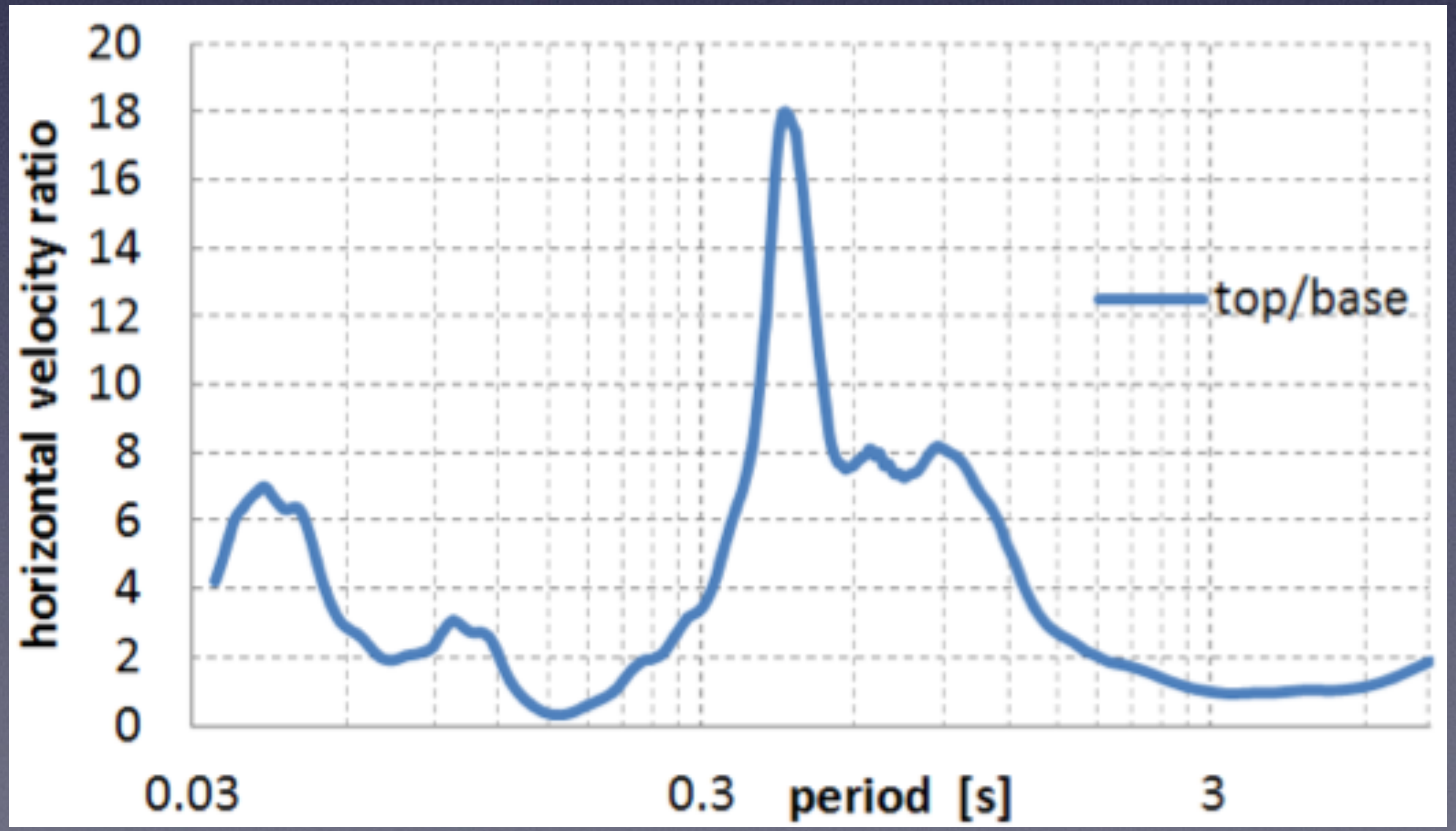
Level 2



Seismic response analysis

Level 3

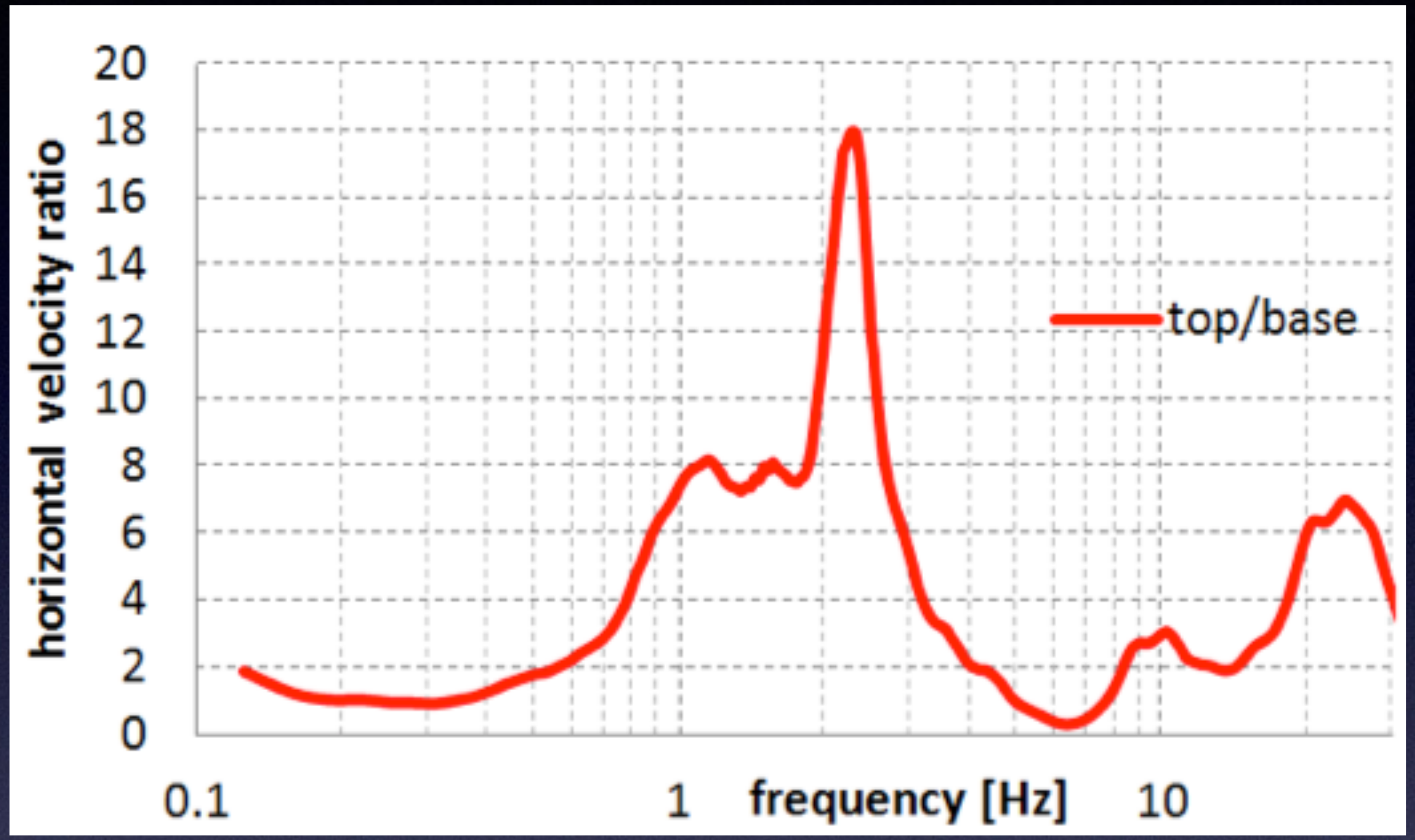




Seismic response analysis

Level 3

Tower



Site