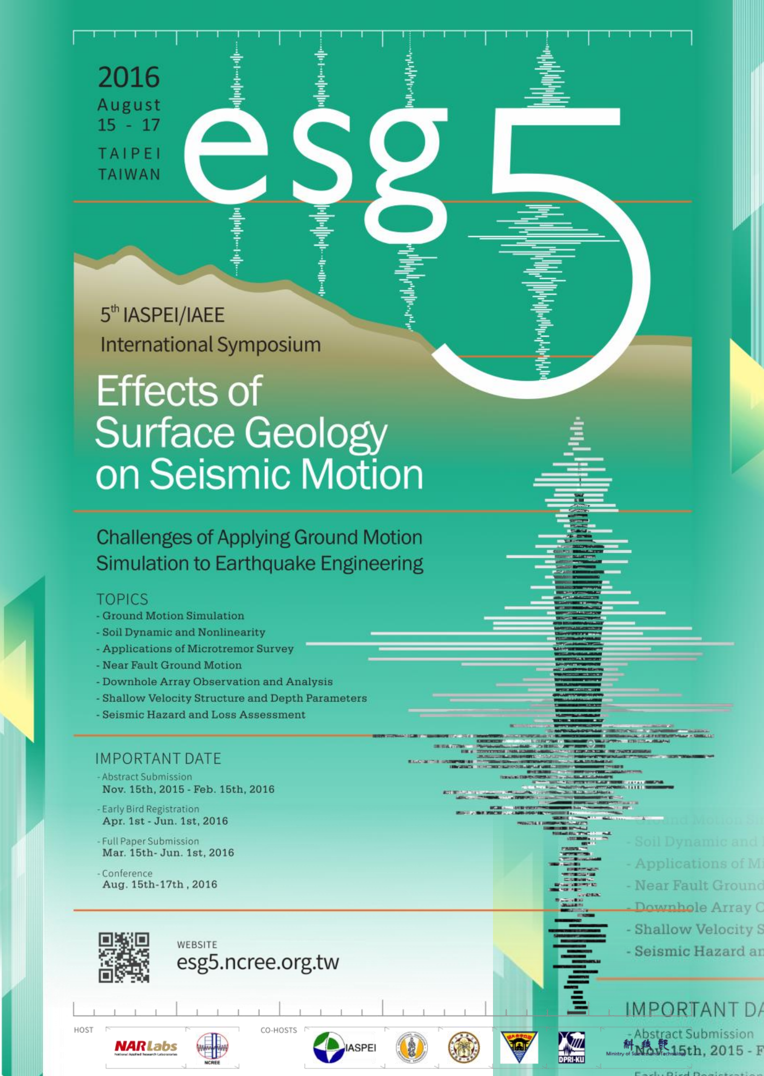


Using Ambient Vibration Measurements for Risk Assessment at Urban Scale : from Numerical Proof of Concept to a Case Study in Beirut (Lebanon)

Christelle Salameh[1], Pierre-Yves Bard[1], Bertrand Guillier[1], Jacques Harb[2], Cécile Cornou[1] and Michelle Almakari[1]

1 - ISTerre, University Grenoble-Alpes, France
2 - Notre-Dame University-Louaizé, Lebanon

Outline

Introduction

- ? Use of frequency information in large scale damage assessment

Conceptual framework and comprehensive numerical simulation

- SDOF elastoplastic oscillators on multilayered 1D (linear) soil profiles
- ANN analysis

Robustness and field applicability

- ? easily available site amplification proxy
- NL soil behavior
- (MDOF)

Sense-check : example Application to Beirut City (Lebanon)

Conclusions, caveats and further steps

Introductory words

- Many examples of larger damage due to coincidence between soil and building frequencies
  - Mexico 1985, Kathmandu 2015, …
  - Obvious for linear systems, not so much for NL systems

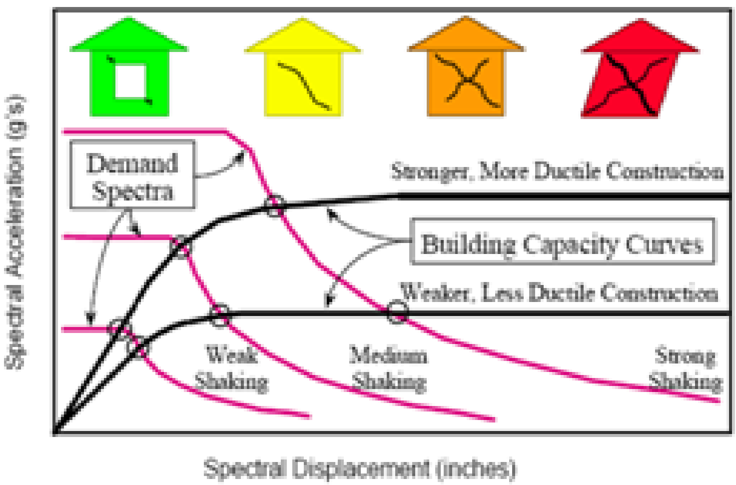
- Building specific studies (detailed information)
  - best GM proxy = SA (f_0) or ASA ([0.6 - 1] f_0)
    - (Perrault & Gueguen, 2015; De Biasio, 2015)

- ? Urban scale (or larger) : Damage / Risk maps
  - Microzonation, site effects : rather quantitative assessment
    - Site characterization : Geology, VS30, f0 (H/V, …)
    - Site amplification
  - Building surveys : most often only qualitative
    - Gross typology

Lack of consistency hazard / vulnerabilty

Damage Estimation

Bullding scale :
Mechanical methods



Purple: Seismic demand
Black: Building Resistance

Large scale (urban) ?
Macroseismic approach (Hazus, RISK-UE)

Individual scale = quantitative

! Challenging !

(spatial variability)

Estimate damages quantitatively on a large scale
with more mechanical input including spectral coincidence

Outline

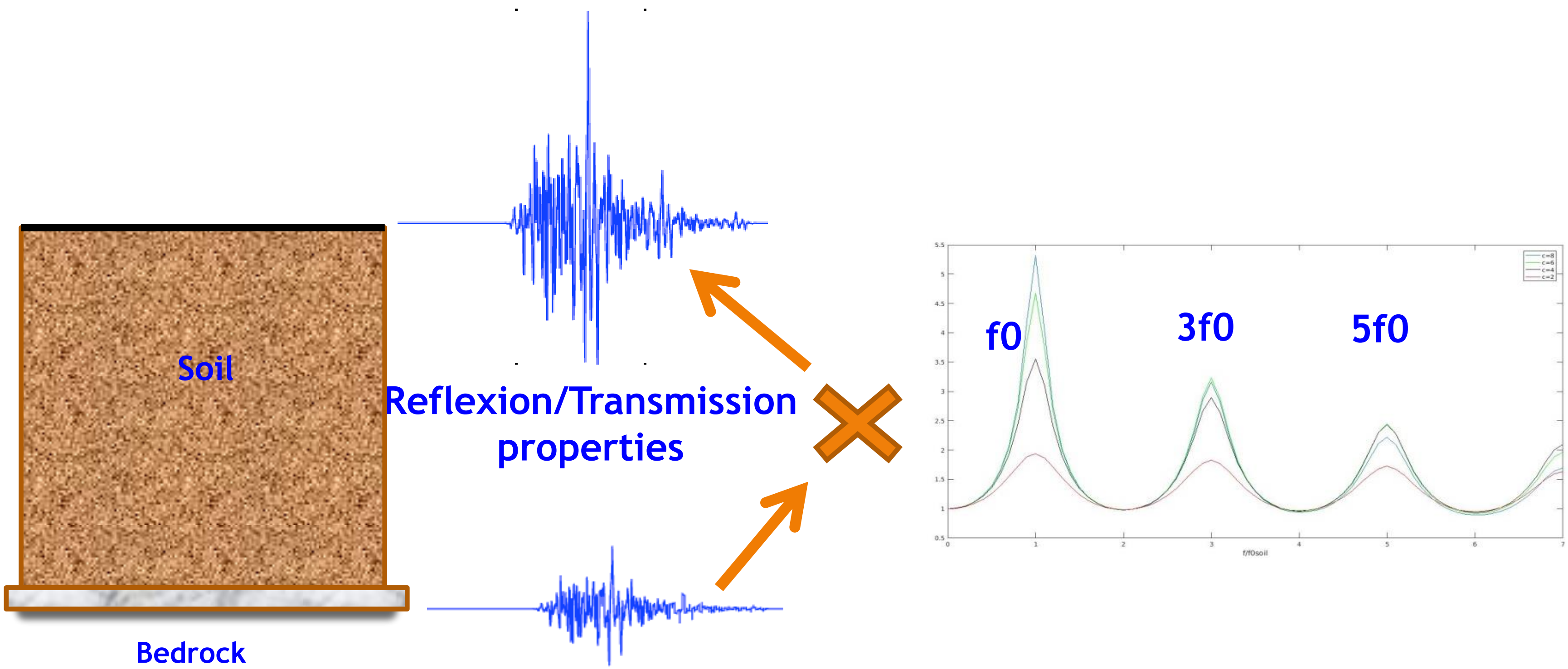
Introduction

- ? Use of frequency information in large scale damage assessment

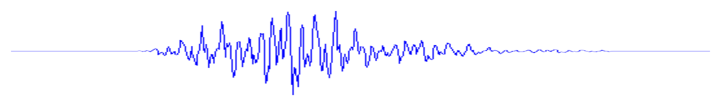
Conceptual framework and comprehensive numerical simulation

- Elastoplastic SDOF oscillator on a single layer
- Extension through comprehensive numerical simulation
  - SDOF elastoplastic oscillators on multilayered 1D soil profiles
- Neural network analysis

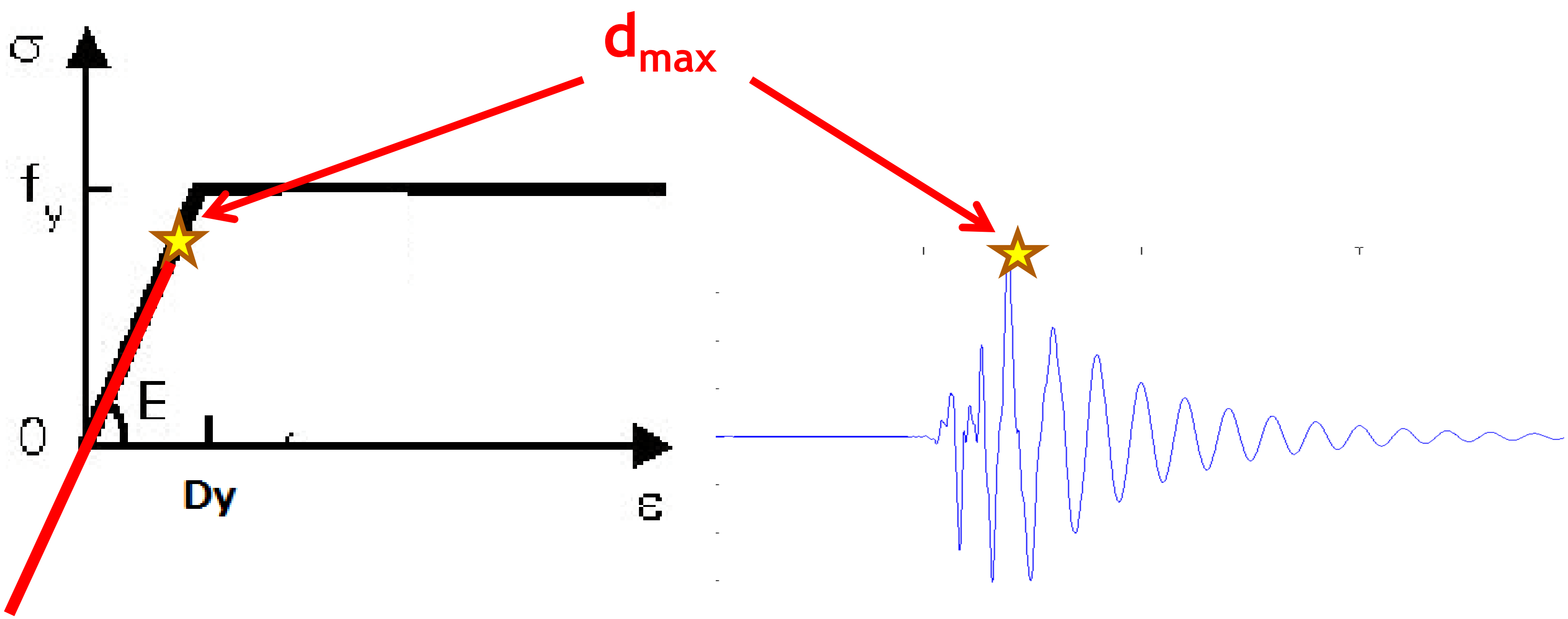
Soil response



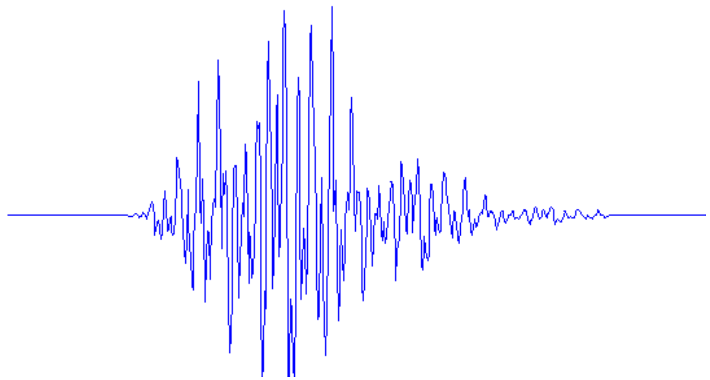
Oscillator response : weak input (linear response)

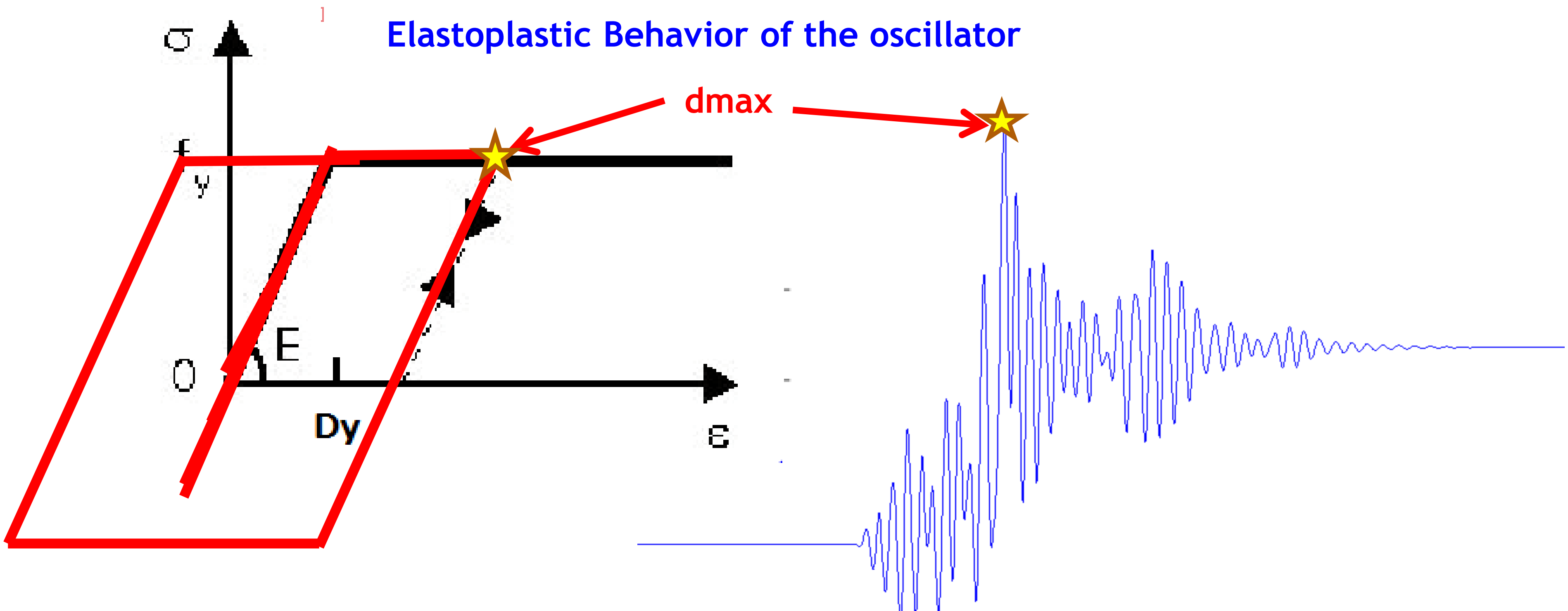


Linear branch of the oscillator

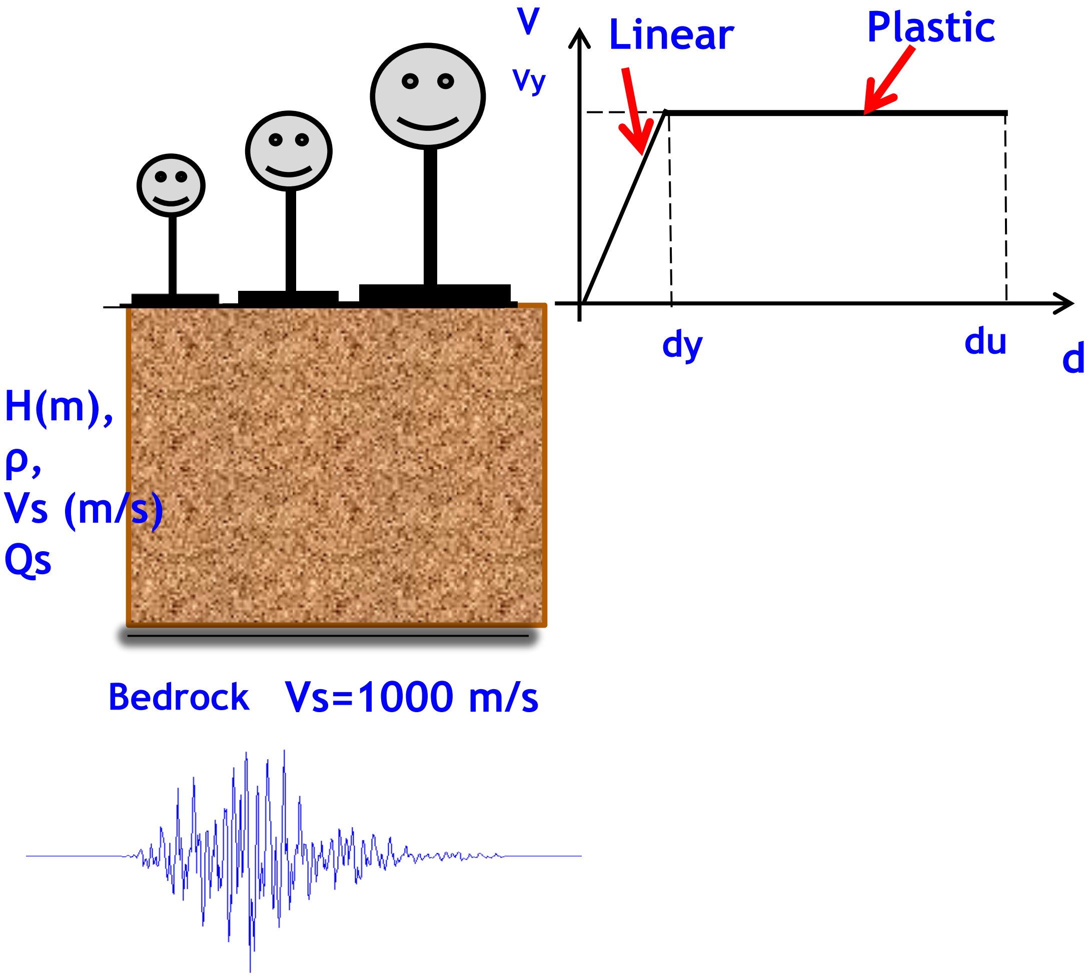


Oscillator response : strong input (non linear domain)





Conceptual framework : a simple illustrative example



54 SDOF Elastoplastic oscillators
- 9 x $f_{structure}$ = 1 → 9 Hz
- 6 x dy= 0.005 → 0.05 (m)

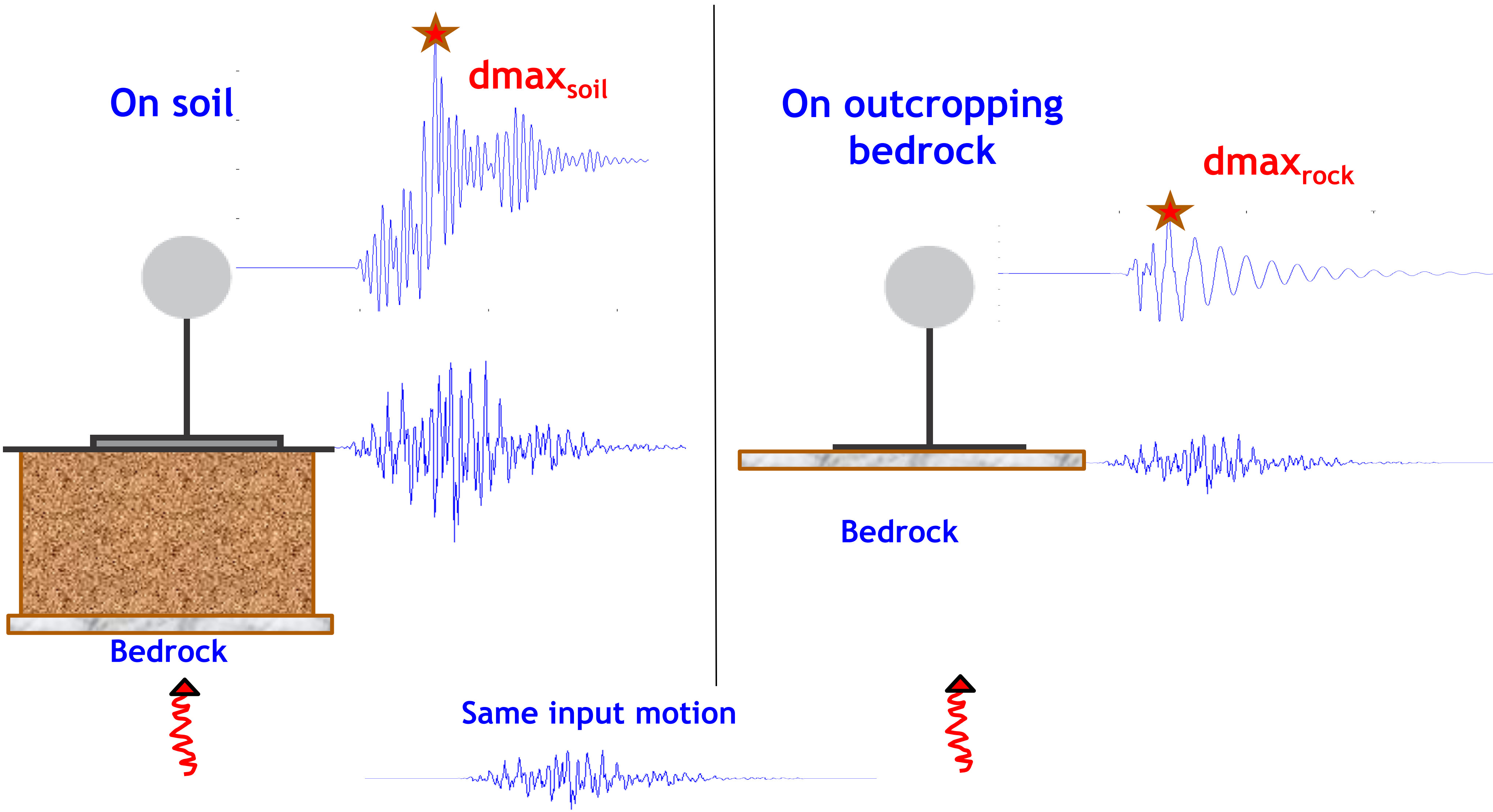
36 Linear single-layer sites (No SSI) :
- 4 x Velocity Contrast= 2 → 8
- 9 x f_{soil}= 1 → 9 (Hz)

60 synthetic Input motion (Sabetta and Pugliese 1996 : nonstationary):
- 5 x Magnitude= 3 → 7
- 4 x Distance= 5 →100 (km)
- PGA= 0.02- 8.6 (m/s^2)

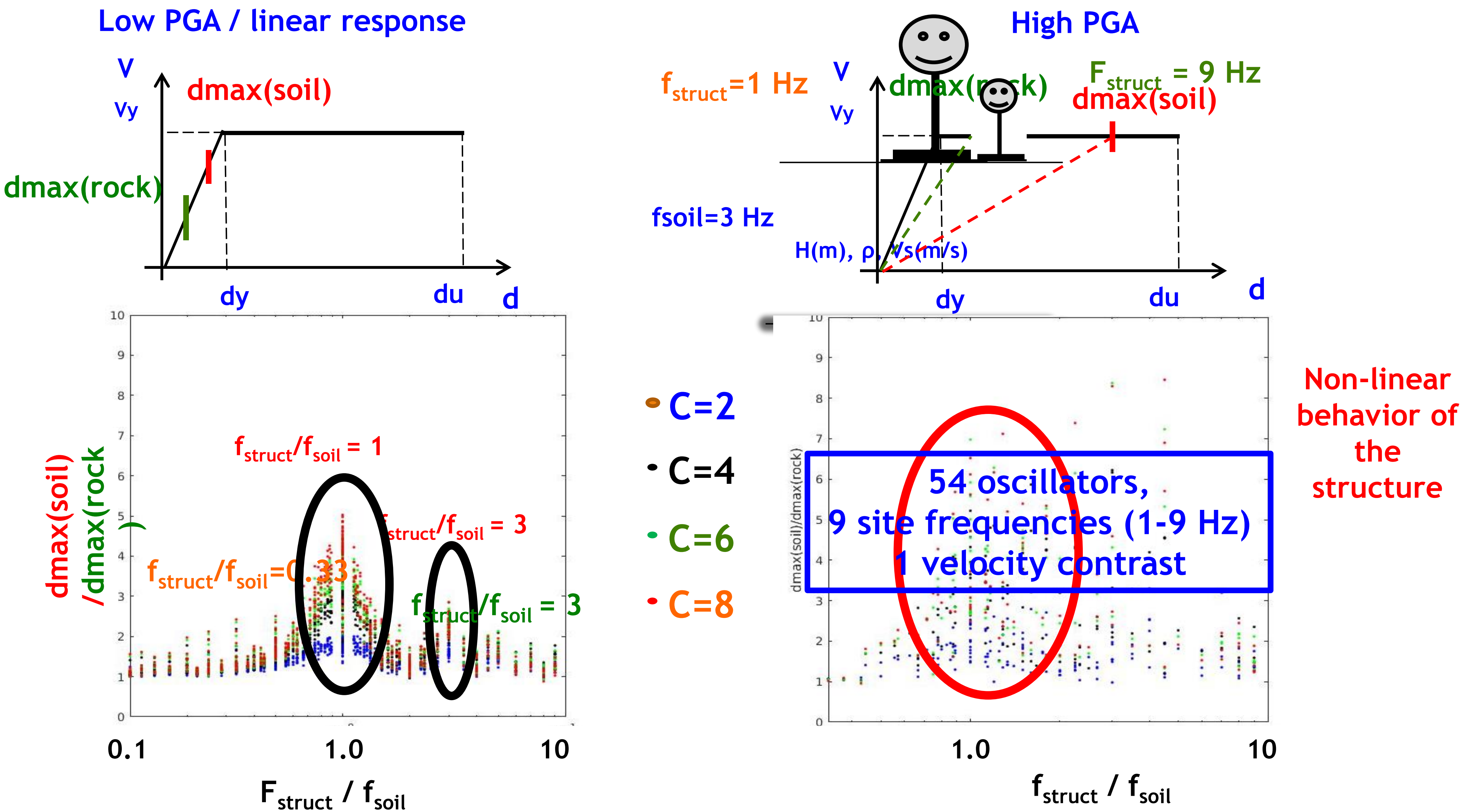
---

116 640 Models

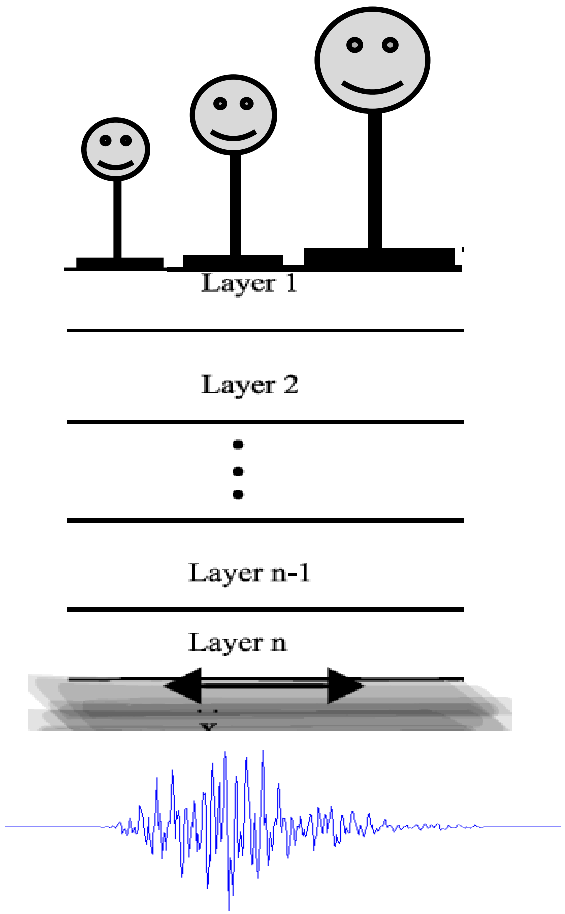
Comparison soil / rock $dmax_{soil}$ / $dmax_{rock}$



Statistical analysis for the simple case



Realistic (less unrealistic...) case: real soil profiles



Risk-UE typologies : 141 SDOF elastoplastic oscillators

f_{struct}, dy, du

classified into 5 typology classes:

1 = Masonry; 2 = Non-designed RC;

3 = RC Low ductility;

4= RC Medium ductility; 5) RC High ductility

887 multilayered linear soils (still no SSI):

614 KiKnet + 251 USA + 22 Europe

f_{soil}= 0.2-39 Hz

Vs30= 111 -2100 m/s

depth= 7-1575 m

60 synthetic Input Signal:

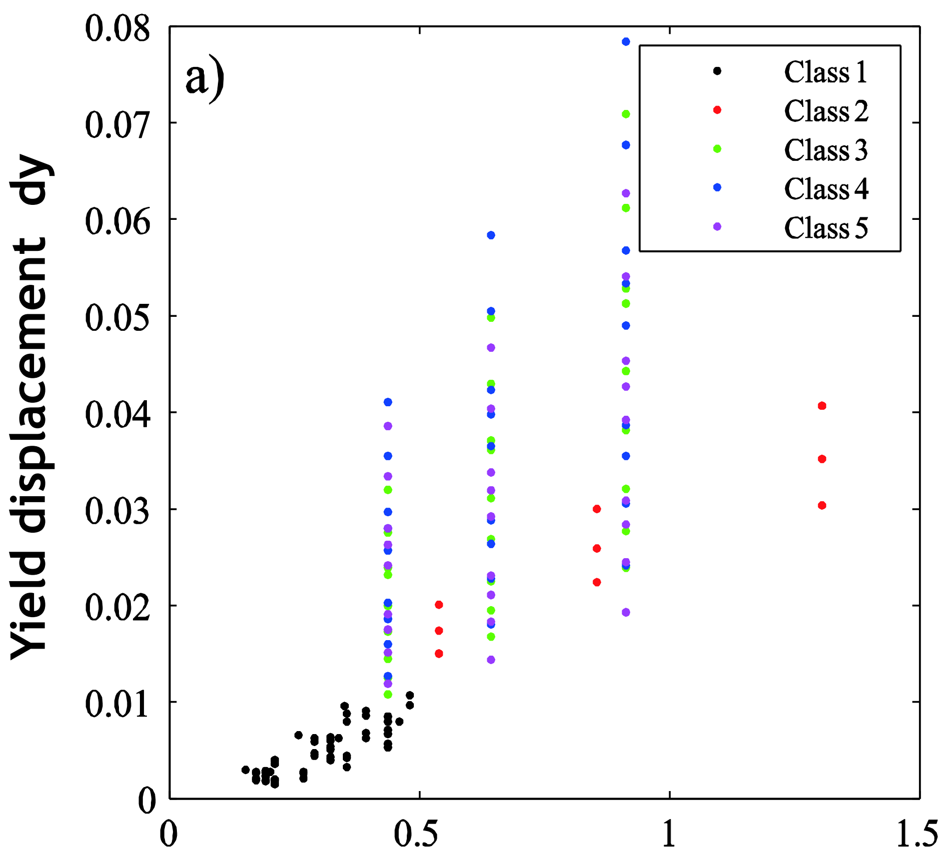
Magnitude= 3 → 7, Distance = 5 →100 km

PGA= 0.02- 8.6 m/s^2

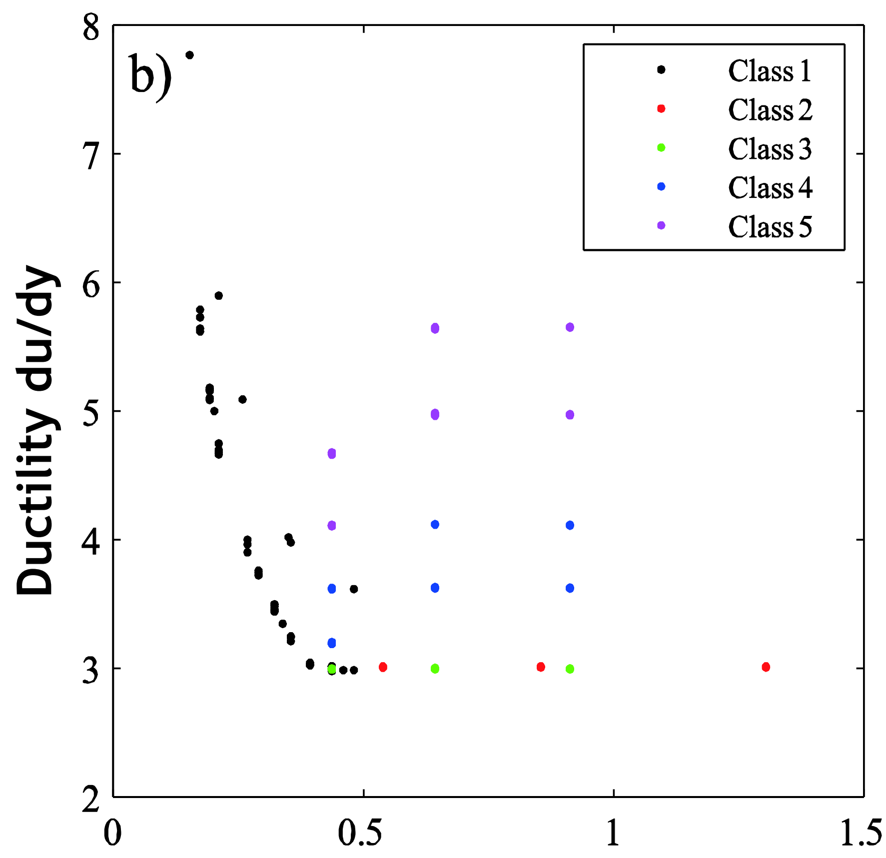
~7.5 MILLION MODELS!!!

Oscillator characteristics

Distribution dy - T_{struct}

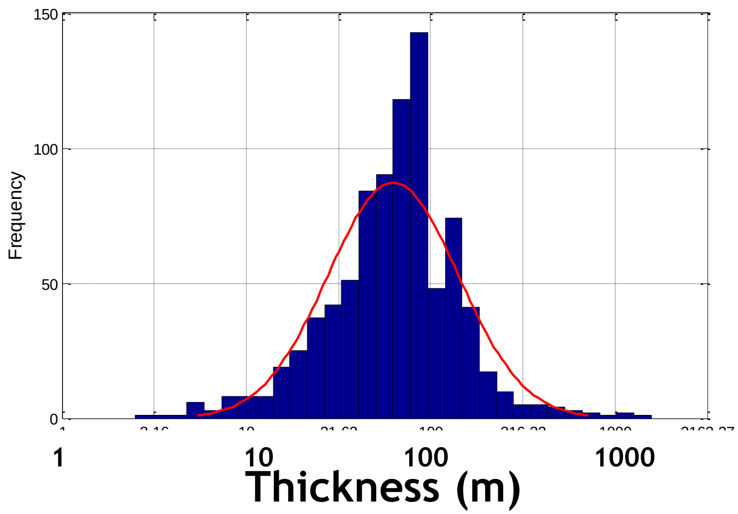


Distribution du/dy - T_{struct}

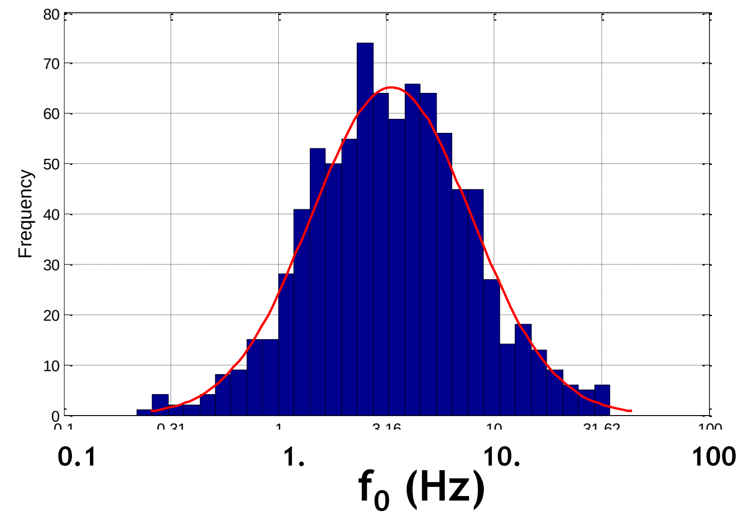


Distribution of site characteristics

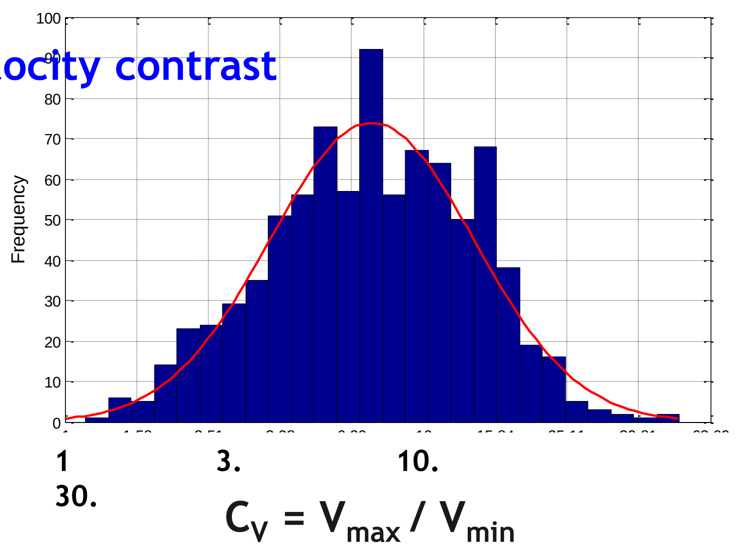
Sediment Thickness

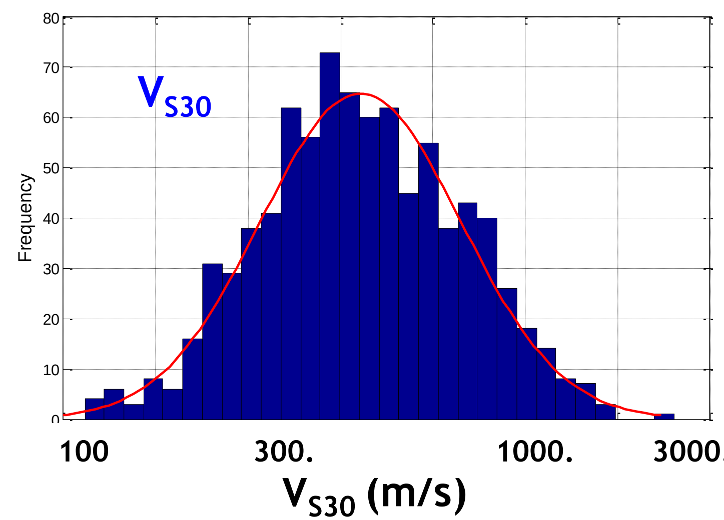


Fundamental frequency



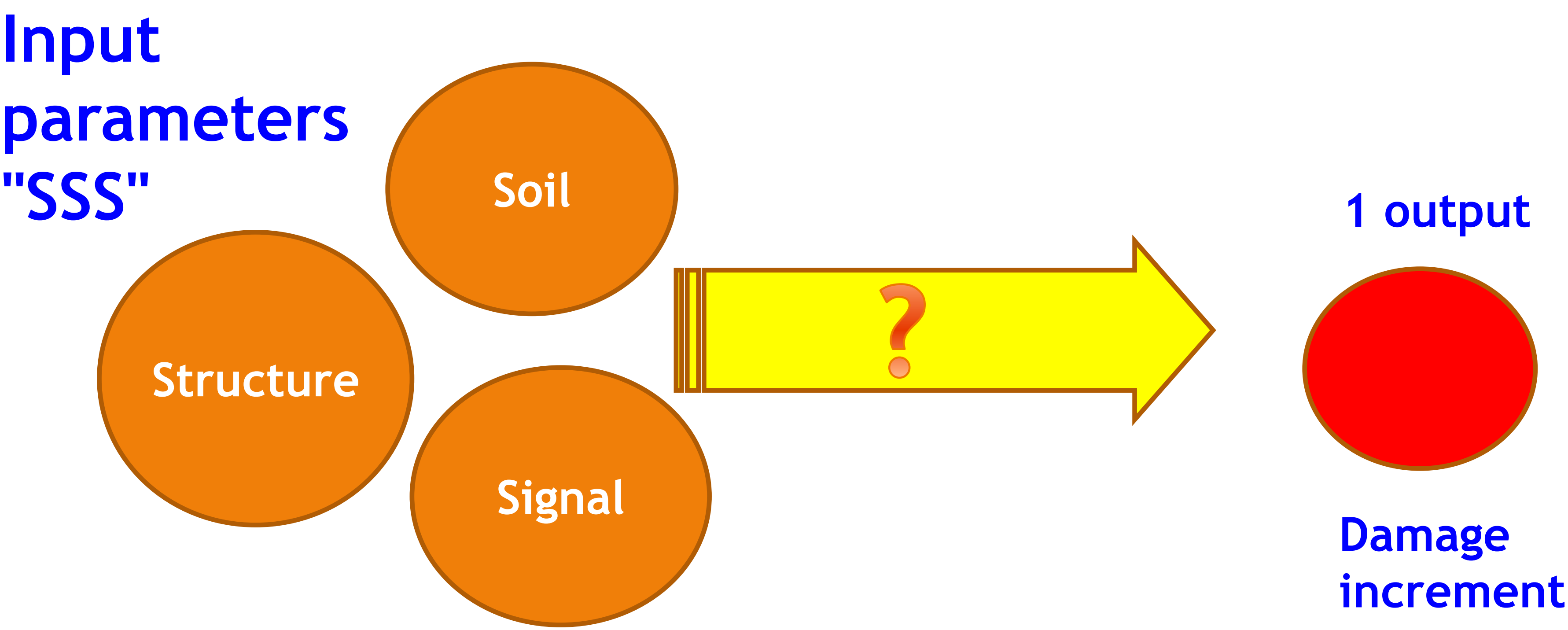
Velocity contrast





Classical statistical analysis?

~7.5 MILLION MODELS!!!



Artificial Neural Network ANN

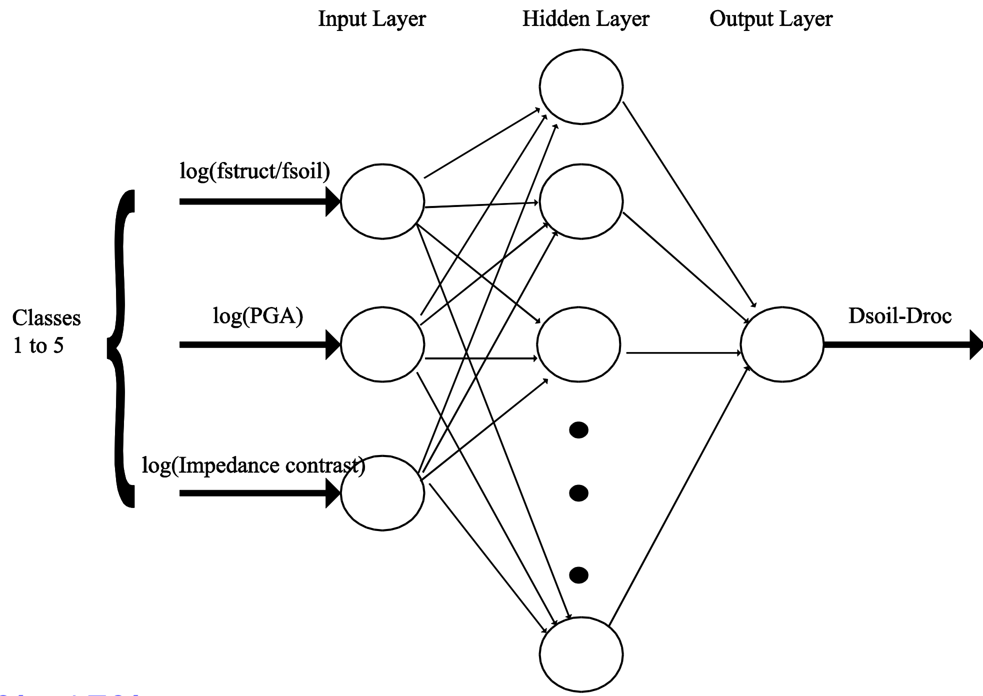
Neural network approach

Goal

- to look for statistical relationships between pre-selected input and output variables, without any a priori on the functional forms

Principle (ML perceptron)

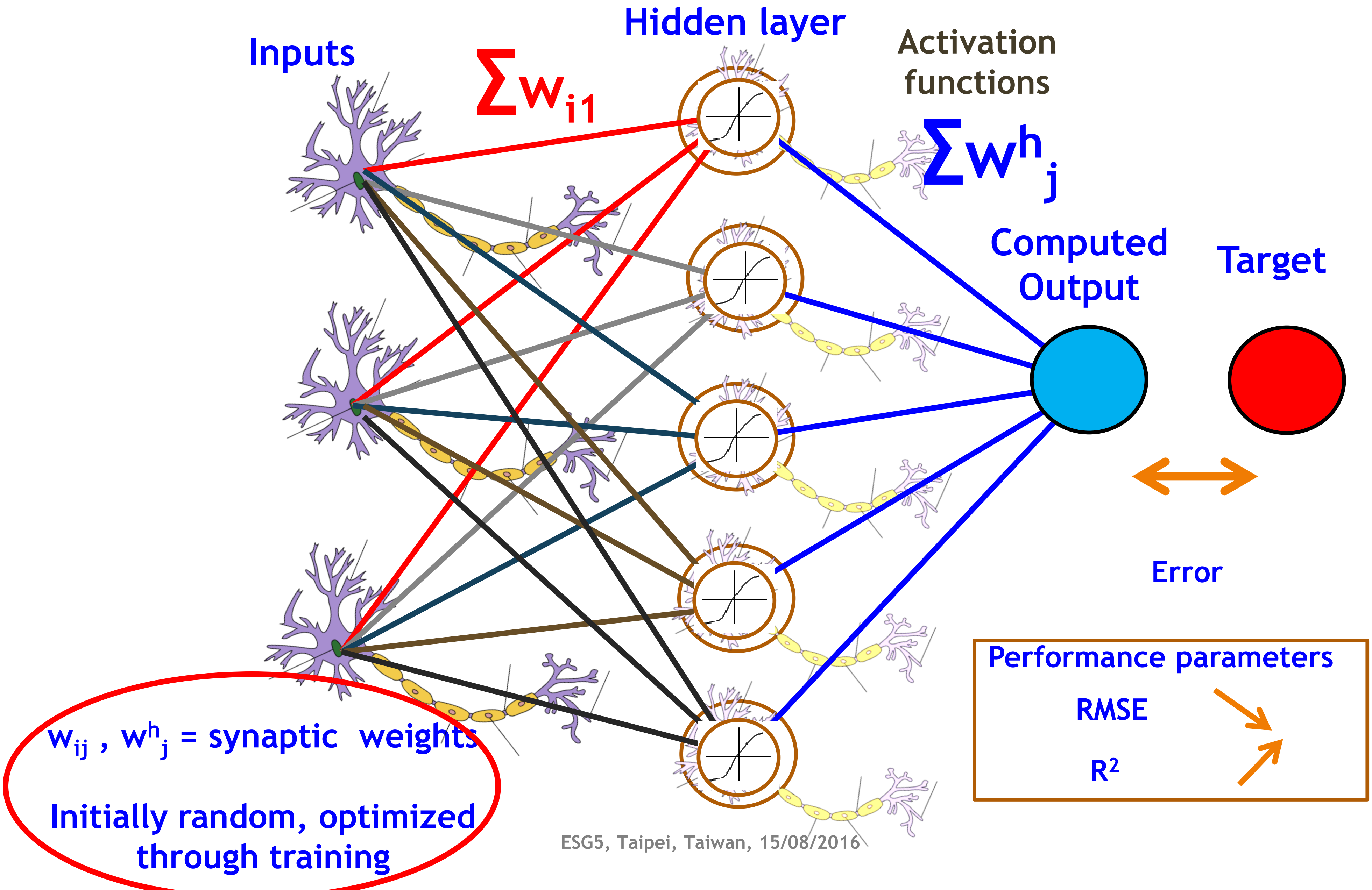
- Combination through weigthed sums ("synaptic weights") and "activation functions"
- Introduction of a "hidden layer"



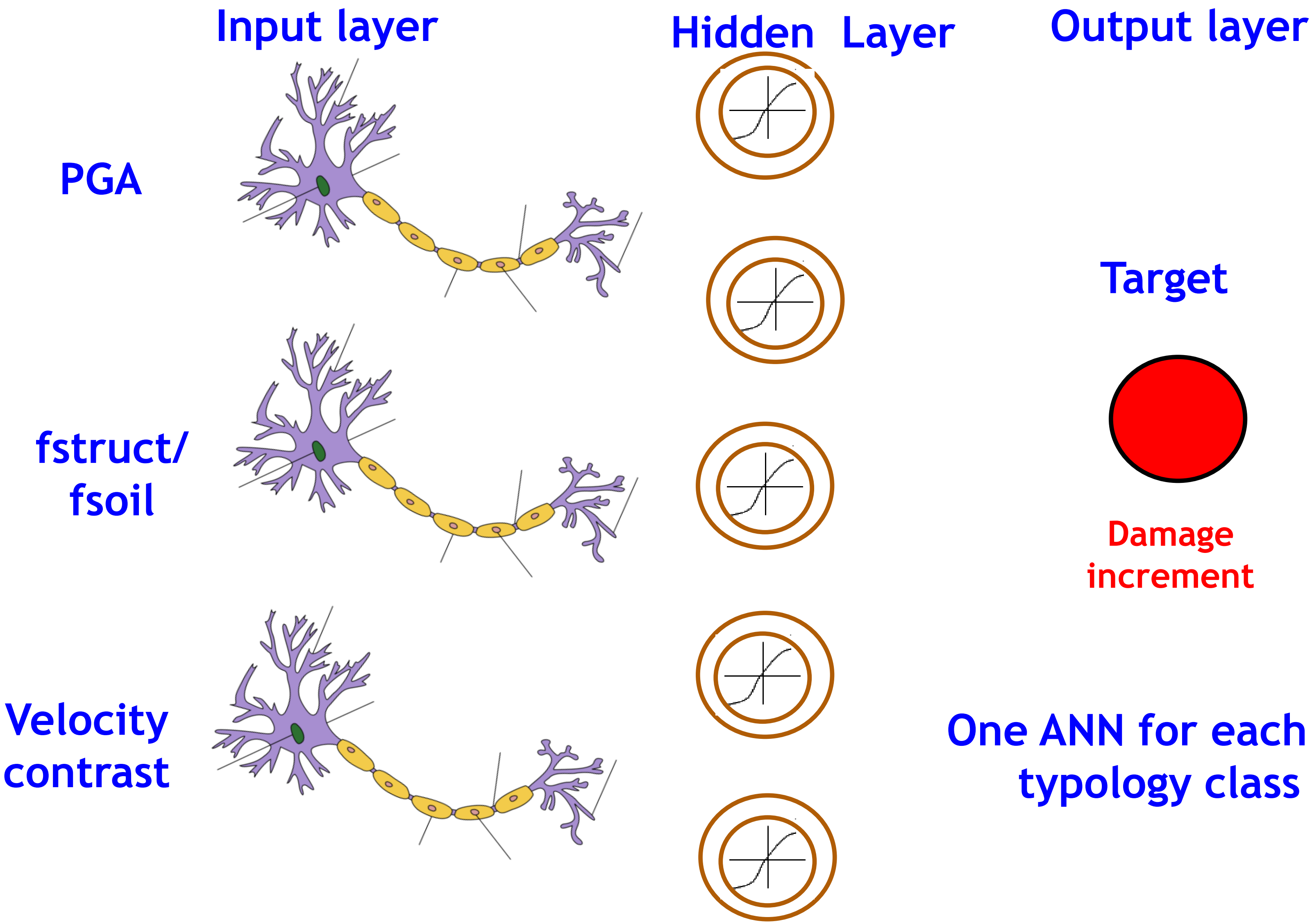
Implementation

- Selection of input and output parameters
- Learning, validation and test sets : 70%, 15%, 15%
- Optimizing
  - Number of neurons in the hidden layer
  - Activation functions
  - Training algorithm

Neural Network : principle

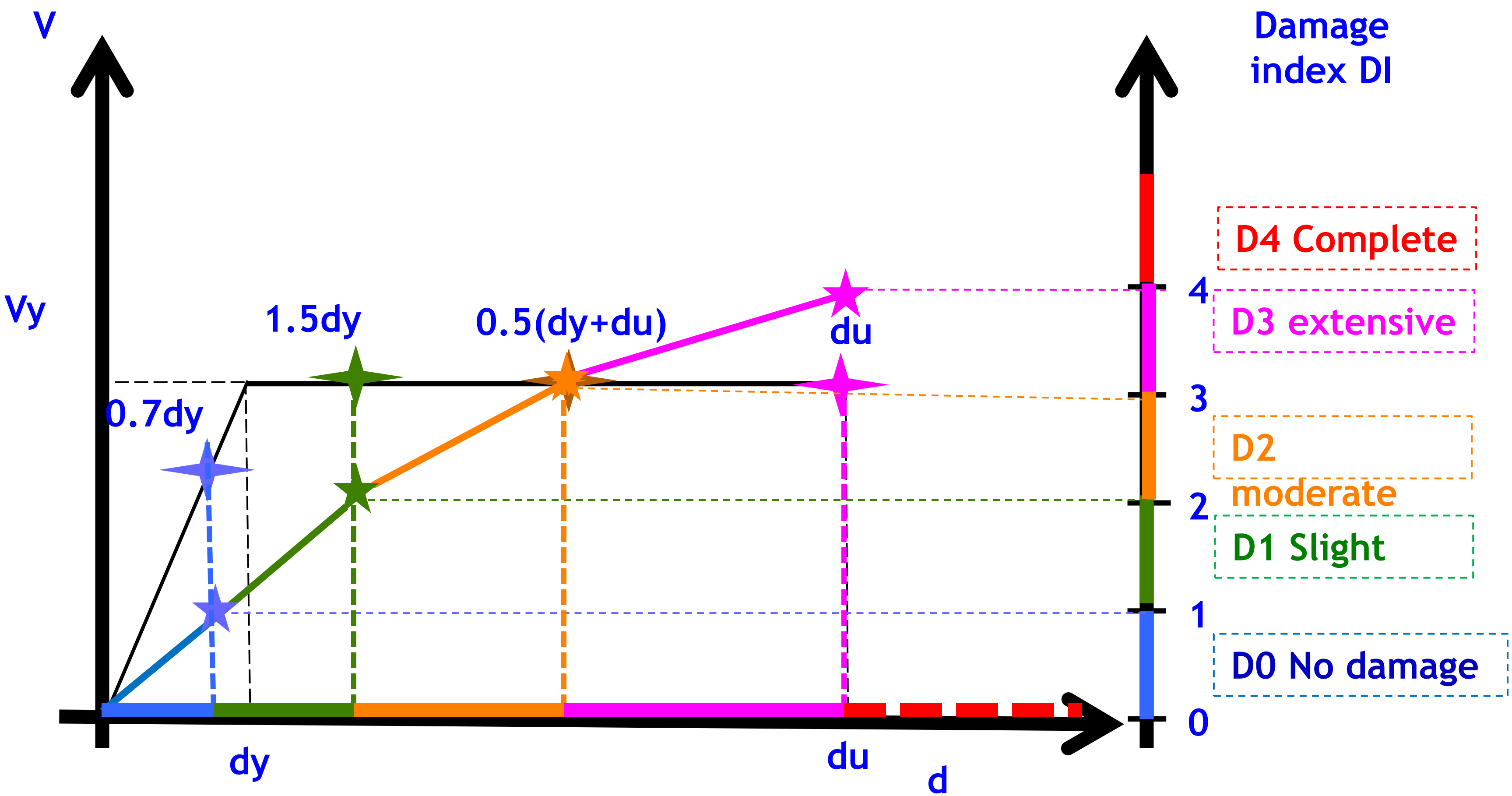


Neural Network: Our case study



One ANN for each building typology class (1-5)

Damage level index



Risk-UE project : correspondence between EMS98 damage states and maximum structural displacement (Lagomarsino and Giovinazzi, 2006)

Performance of the ANN models

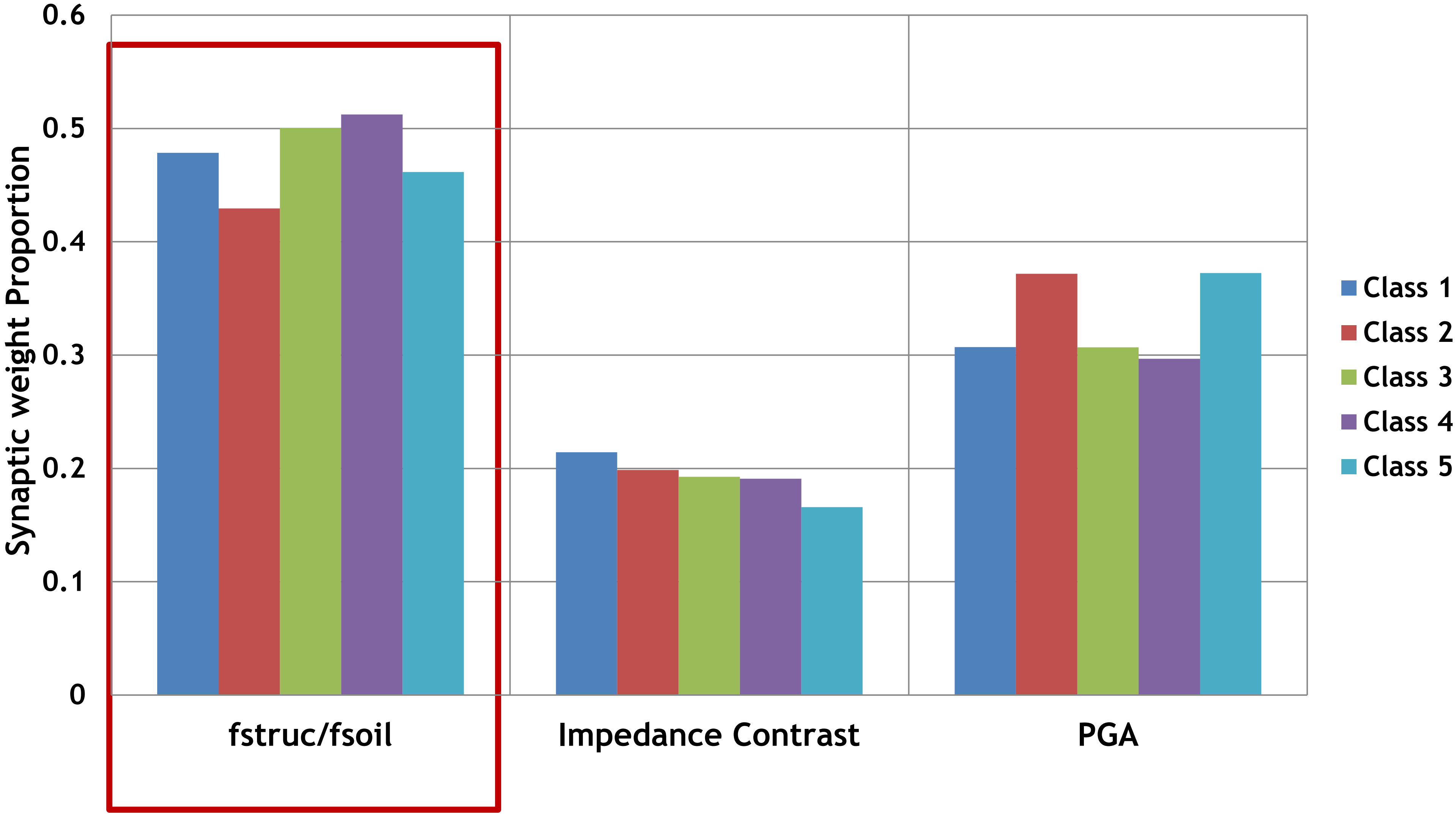
ANN Model / Vulnerability Class	Initial standard deviation	Error RMSE	RMSE Reduction	Variance reduction	Coeffificient of determination R^2
Class 1 (Masonry)	0.182	0.126	31%	52%	0.81
Class 2 (Non-designed RC)	0.170	0.102	40%	64%	0.80
Class 3 (Low ductility RC)	0.172	0.112	35%	58%	0.81
Class 4 (Medium ductility RC)	0.153	0.094	39%	62%	0.81
Class 5 (High ductility RC)	0.147	0.096	35%	57%	0.82

Variance Reduction 50-64% + Good R^2

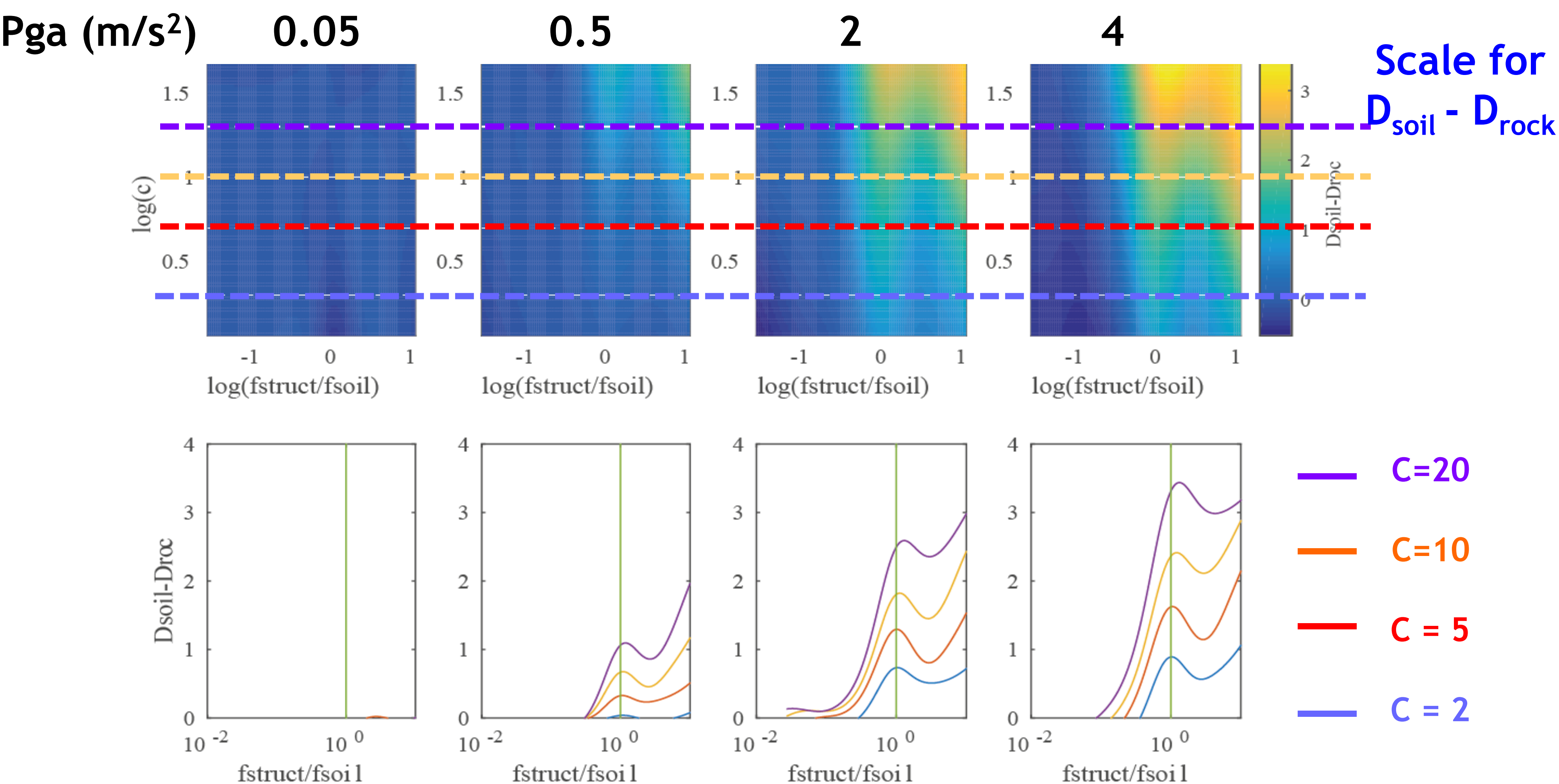
⇩

Satisfactory performance
(given the small number of input parameters)

Relative importance of input parameters : synaptic weights



Dependence of damage increment on SSS inputs (example: class 3 - Low Ductility RC)



Outline

Introduction

Proof of concept : comprehensive numerical simulation

Robustness and field applicability

- Field applicability : site amplification proxy
- NL soil behavior
- (MDOF)

Fiel applicability : Input parameters

Loading : PGA ✔

Spectral coincidence : fstruct / fsoil ✔

Building mechanical behavior : typology class ✔

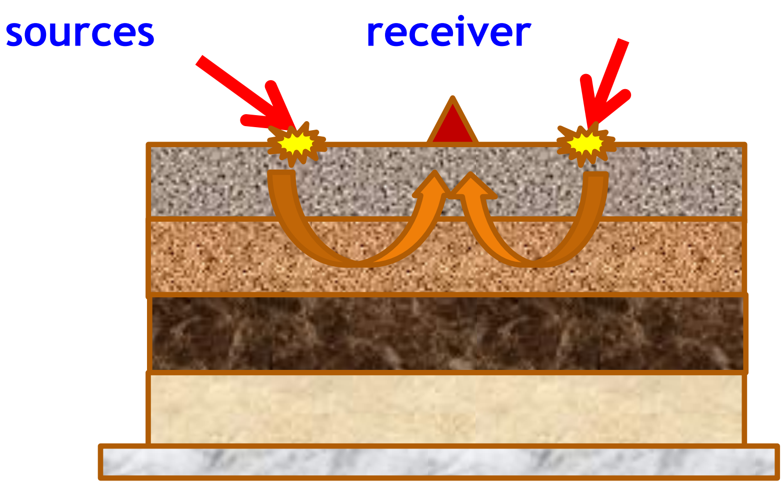
Site amplification : velocity contrast Cv ✗

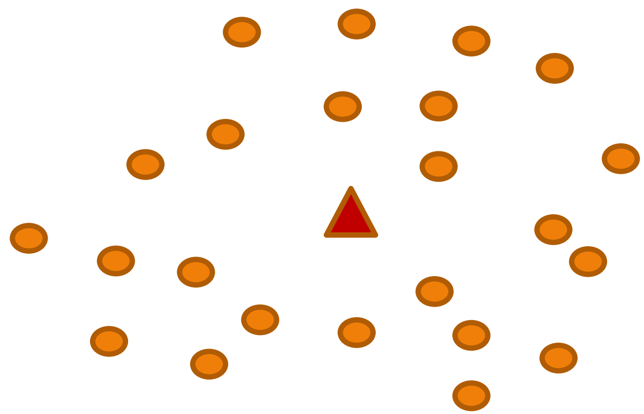
- ? Other site amplification proxies : V_{S30}, V_{S10}, A_{0HV}, ...

Numerical simulation of ambient noise

After Bonnefoy-Claudet et al., (2006)

Step 1: Definition of sources-receiver configuration

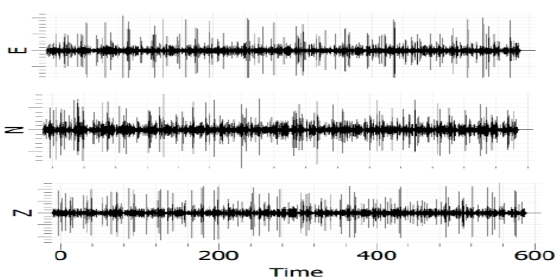




Step 2: Computation of Greens functions : DWN

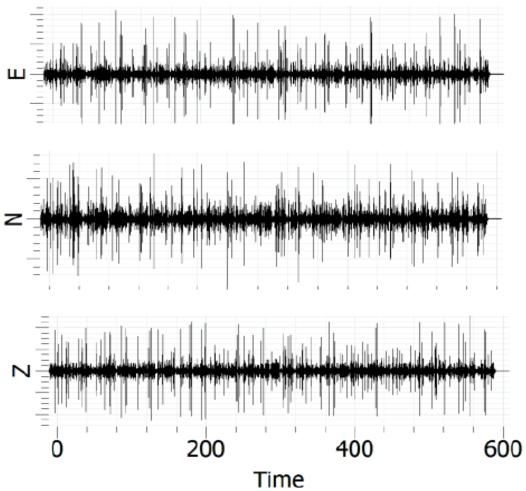
[Hisada, 1995]

Step 3: Summation of all the individual noise synthetics in the time domain.

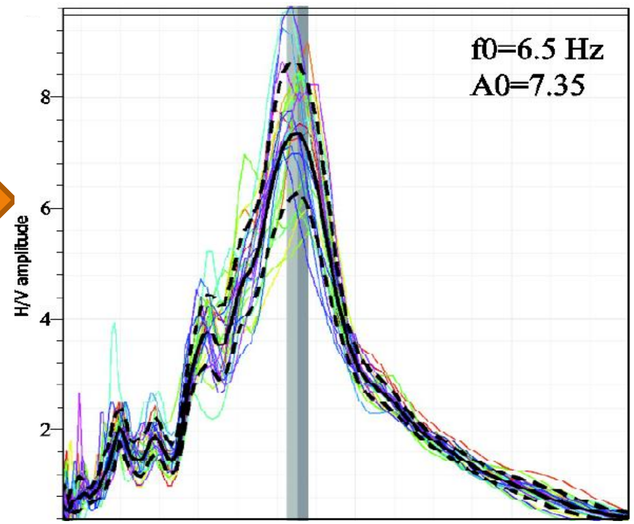


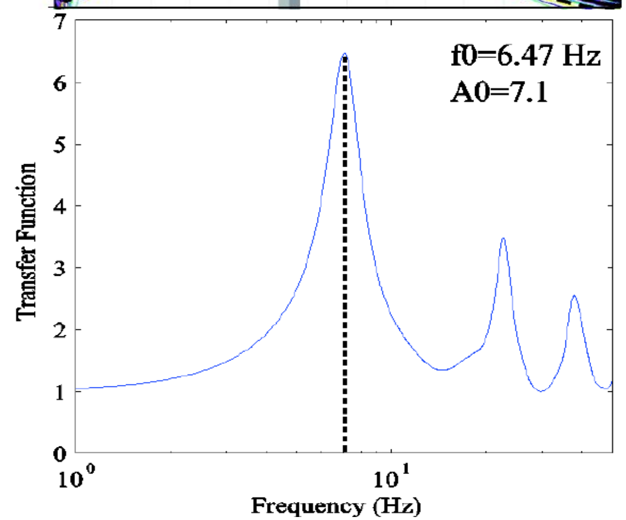
Total ambient noise synthetics for each of the 887 soil profiles (5-10 min)

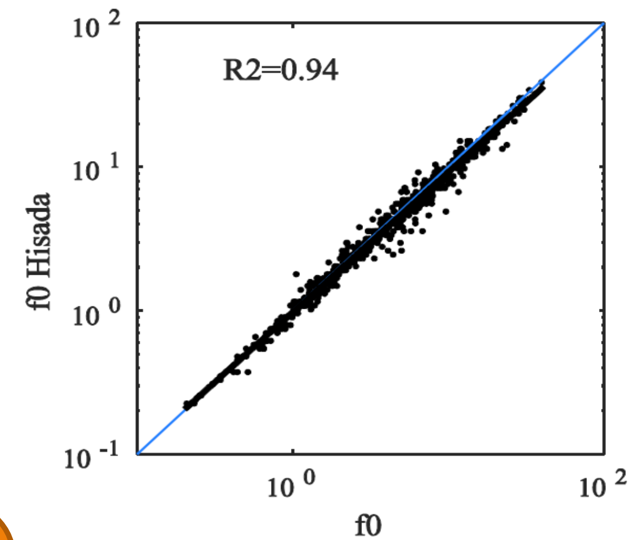
Derivation and check
of the "expected" H/V spectral ratio

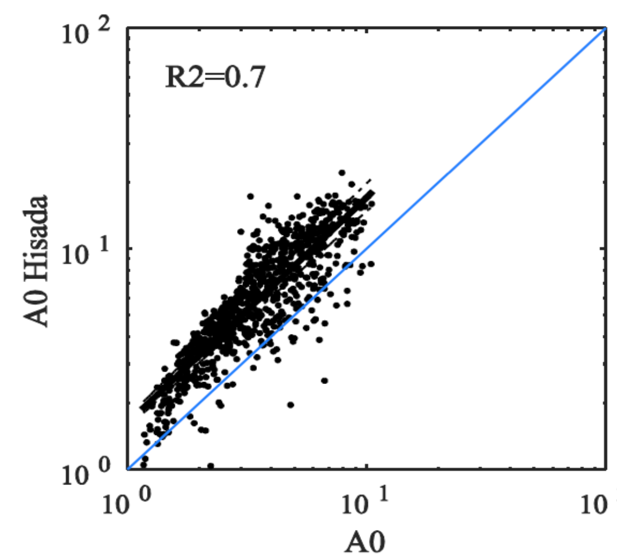


Geopsy

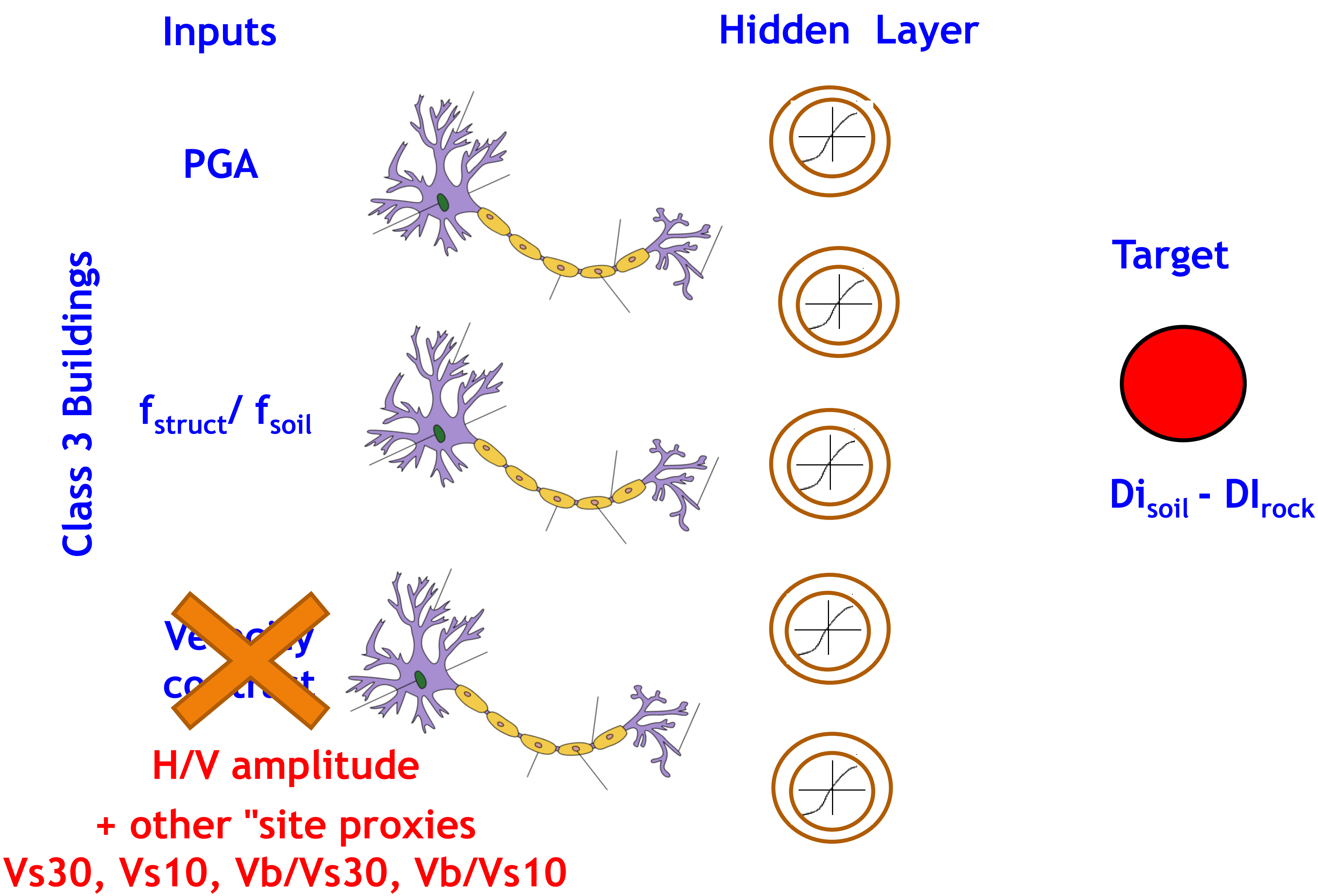




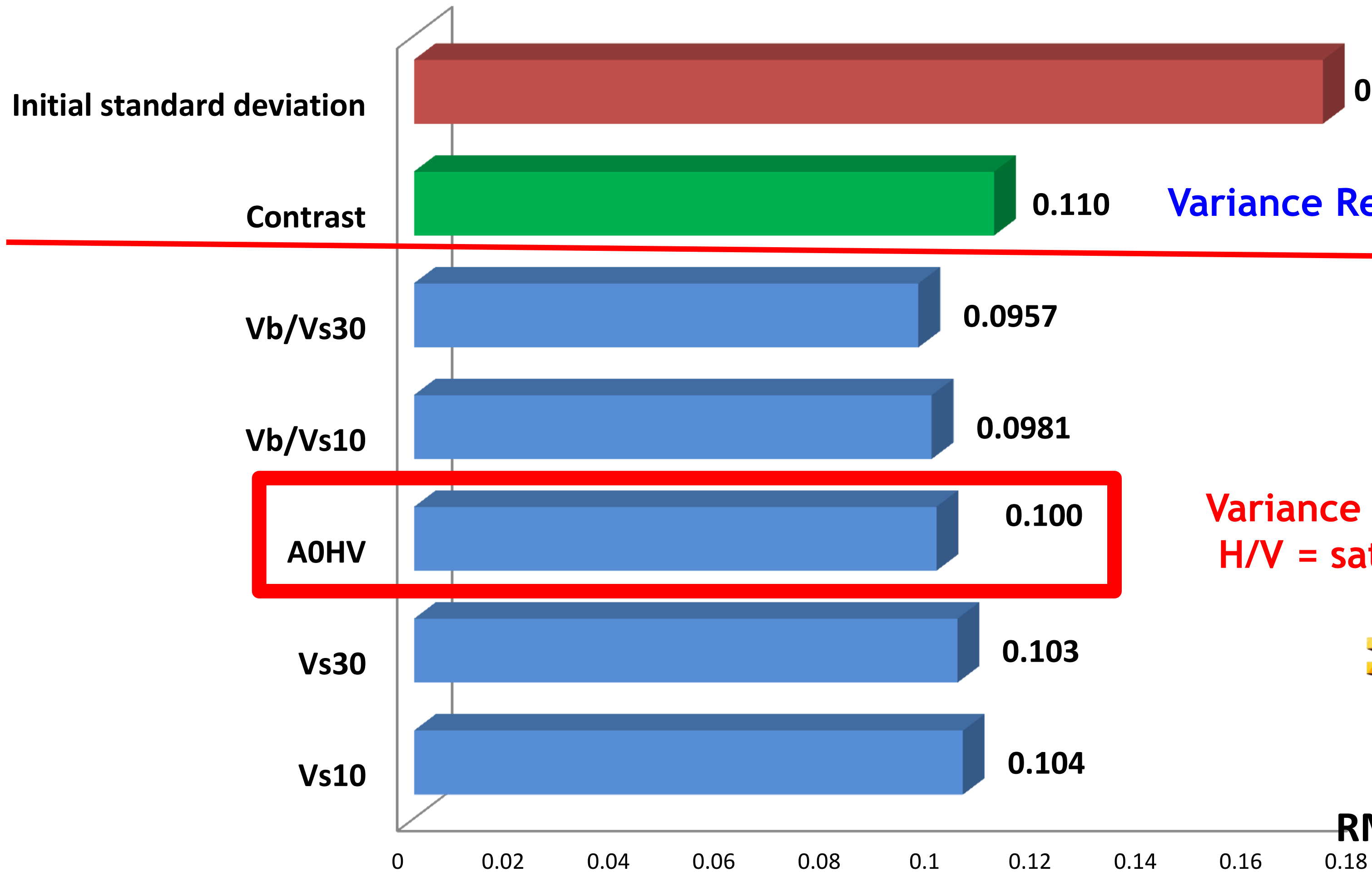




Modified Neural Network



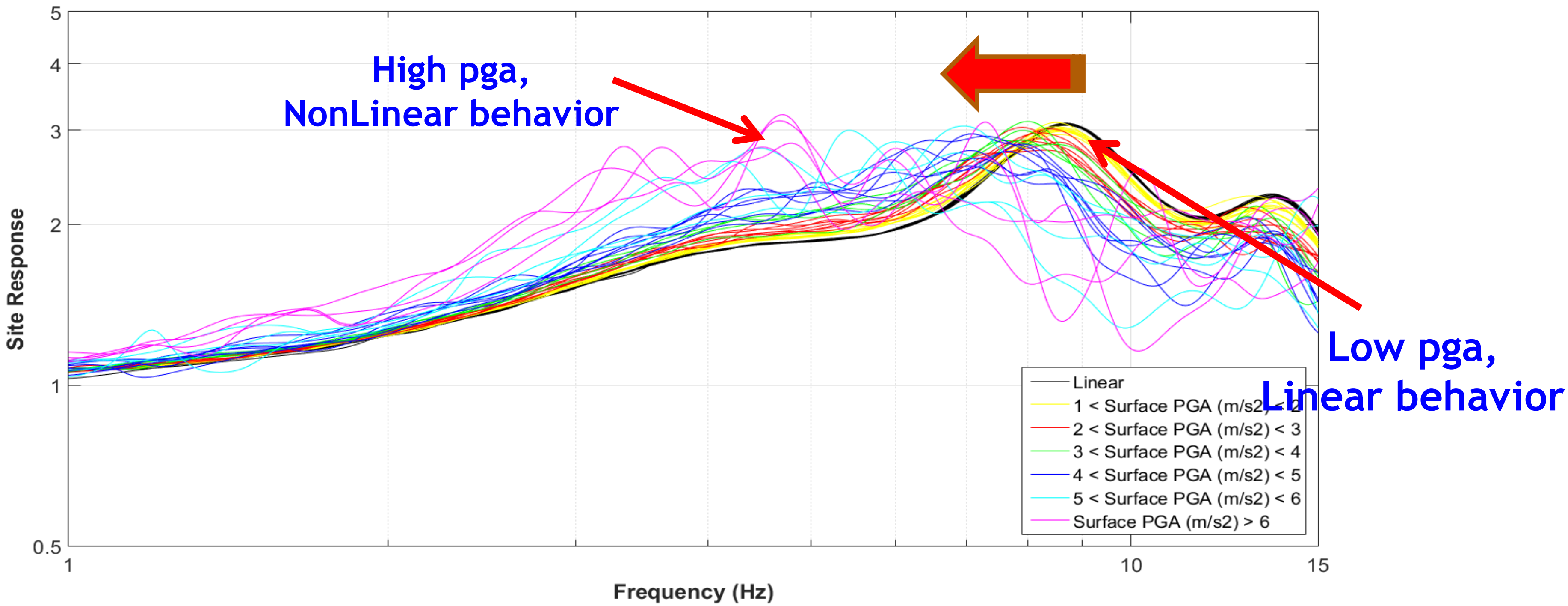
Performance of each site amplification proxy : RMSE



Variance reduction = 66%
H/V = satisfactory proxy

Robustness : accounting for soil non-linear response

Evolution of site transfer functions with PGA *(see also Almakari et al., ESG5 2016)*



Shift of frequency towards lower values
+ decrease of amplification

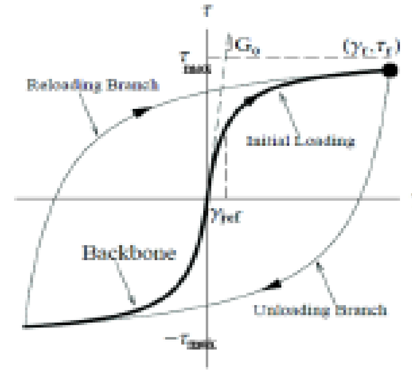
Nonlinear simulations

Finite difference software: NOAH

(Bonilla 2001)

Time domain, Hysteretic behavior

887 profiles



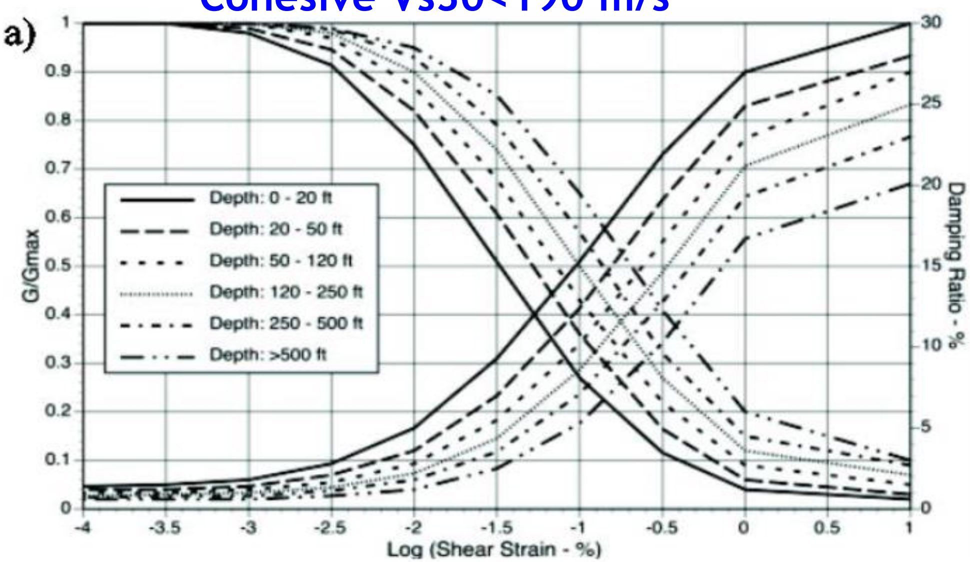
$$\frac{G}{G_0} = \frac{1}{1 + \left|\frac{\gamma_{xy}}{\gamma_{ref}}\right|}$$

$$\gamma_{ref} = \frac{\tau_{max}}{G_0}$$

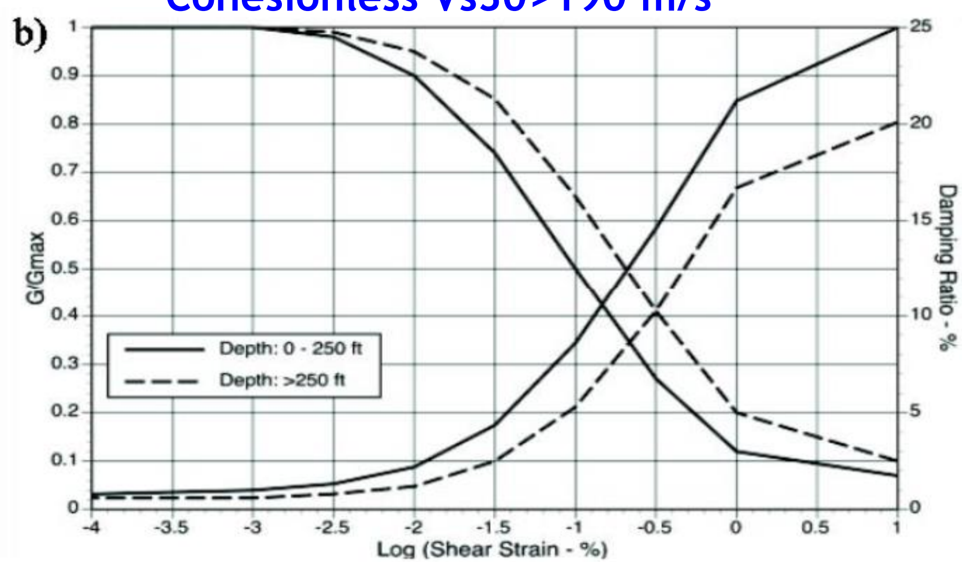
Site NL characteristics

PEER NGAW2 assumptions (Kamai et al., 2014)

Cohesive Vs30<190 m/s



Cohesionless Vs30>190 m/s



New neural network

(Class 3)

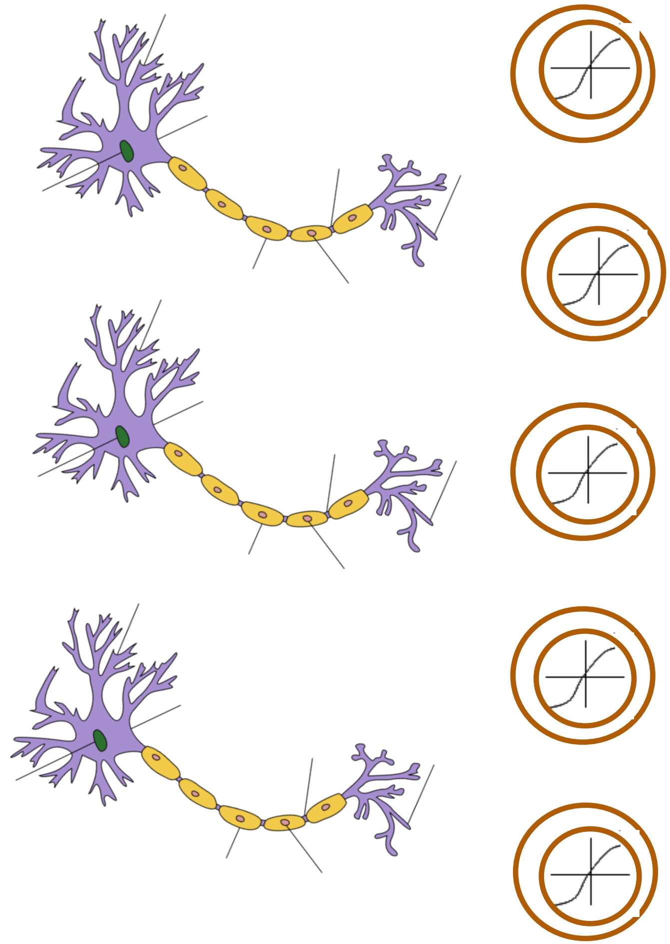
Inputs

PGA

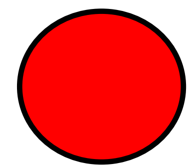
f_{struct}/ f_{soil}

Velocity contrast

Hidden Layer



Target



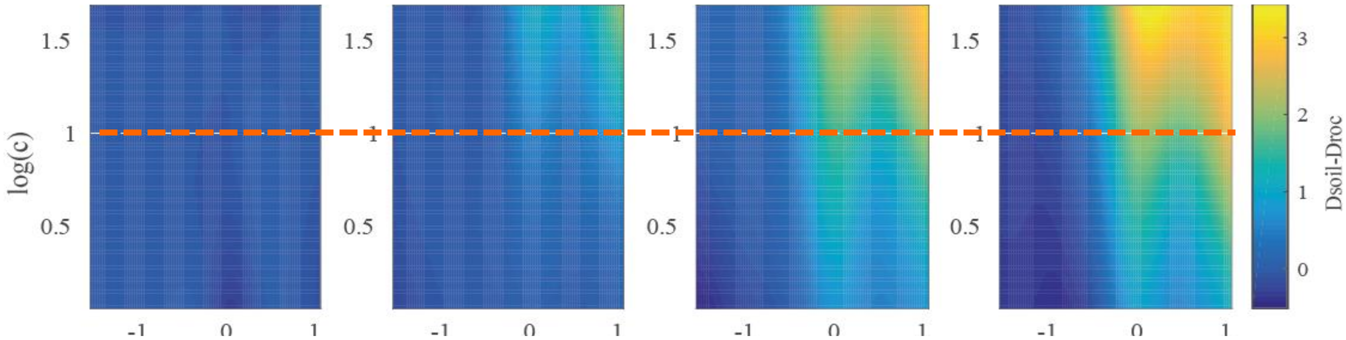
Modified D_{soil} - D_{rock}

Site Non-linear response + recomputation of oscillator response on soil

Results with NL soil for building typology class 3

Pga (m/s^2) : 0.05 0.5 2 4

Linear



Scale for D_{soil} - D_{rock}

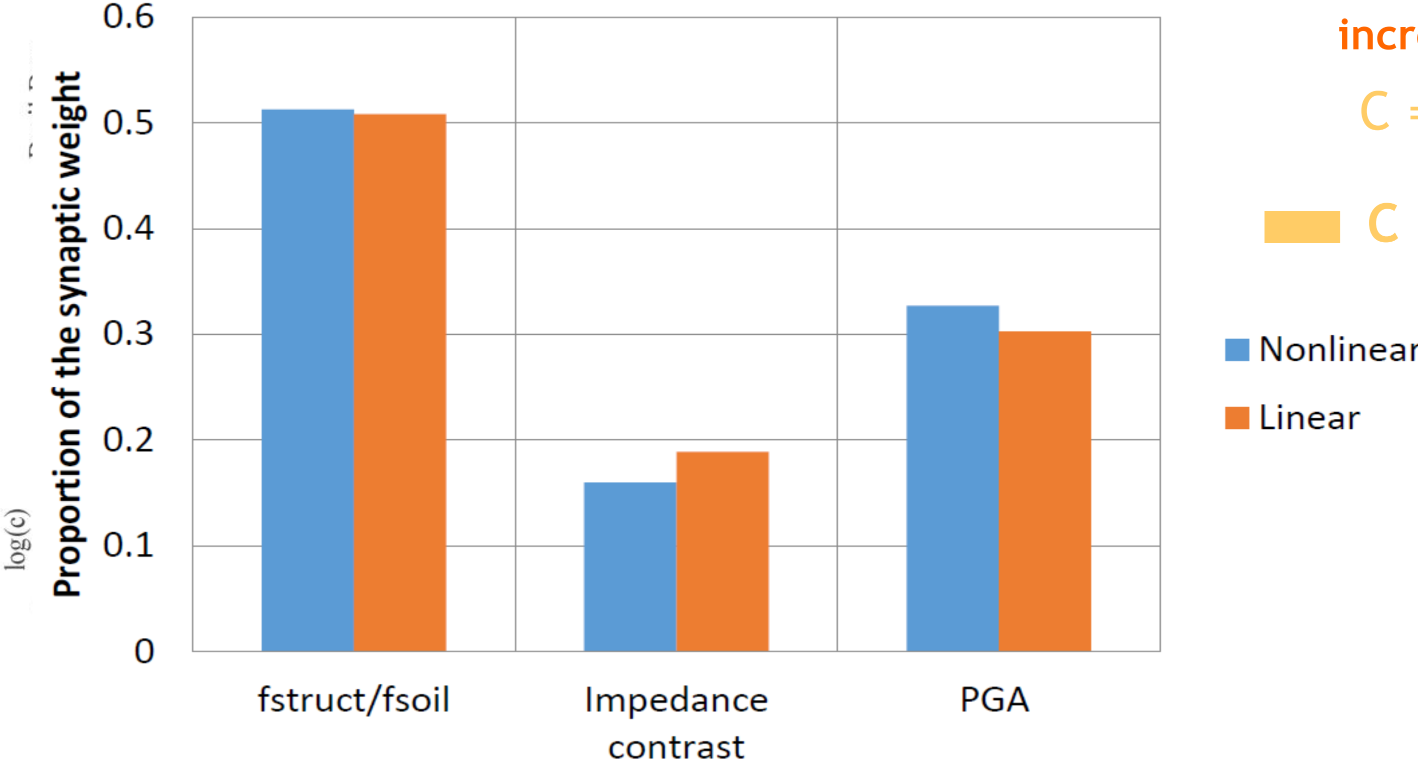
Slight modification (shift of frequency, reduction of the amplitude), but f_{struct}/f_{soil} remains the predominant parameter

Damage increment

C = 10, L

C = 10, NL

Non-Linear



Summary of ANN performances

		Model 1 velocity contrast, linear site response	Model 2 H/V amplitude, linear site response	Model 3 Non-linear site response, impedance contrast
Site amplification proxy		$C = V_{max}/V_{min}$	A_{0HV}	$C = V_{max}/V_{min}$
Performance indicators	Standard deviation (initial value : 0.1724)	0.112	0.099	0.103
	Coefficient of determination R^2	0.81	0.86	0.82
Synaptic weights	f_{struct}/f_{soil}	0.51	0.51	0.51
	Site amplification proxy	0.19	0.20	0.16
	PGA	0.30	0.29	0.33

Outline

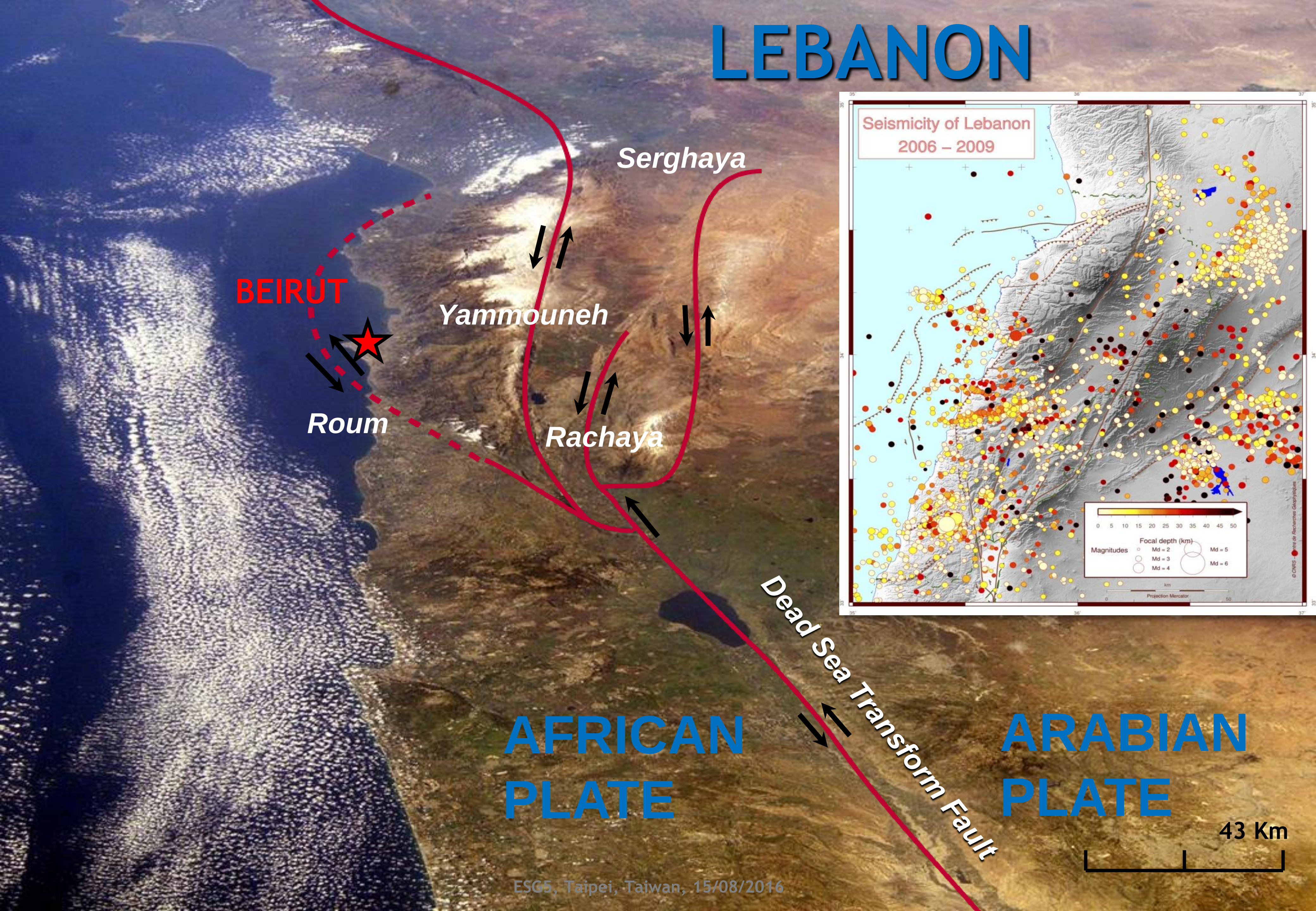
Introduction

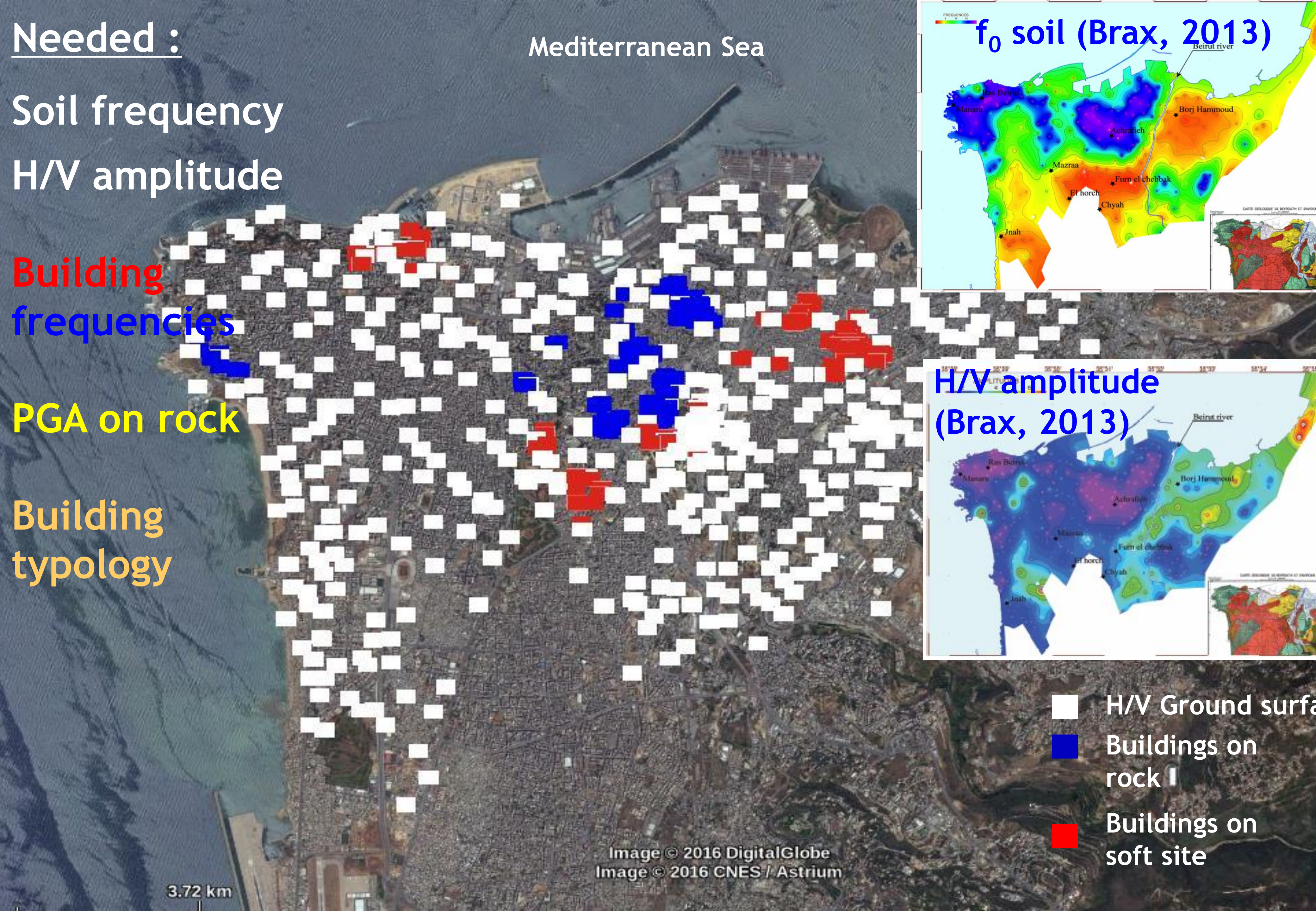
Conceptual model and comprehensive numerical simulation

Robustness and field applicability

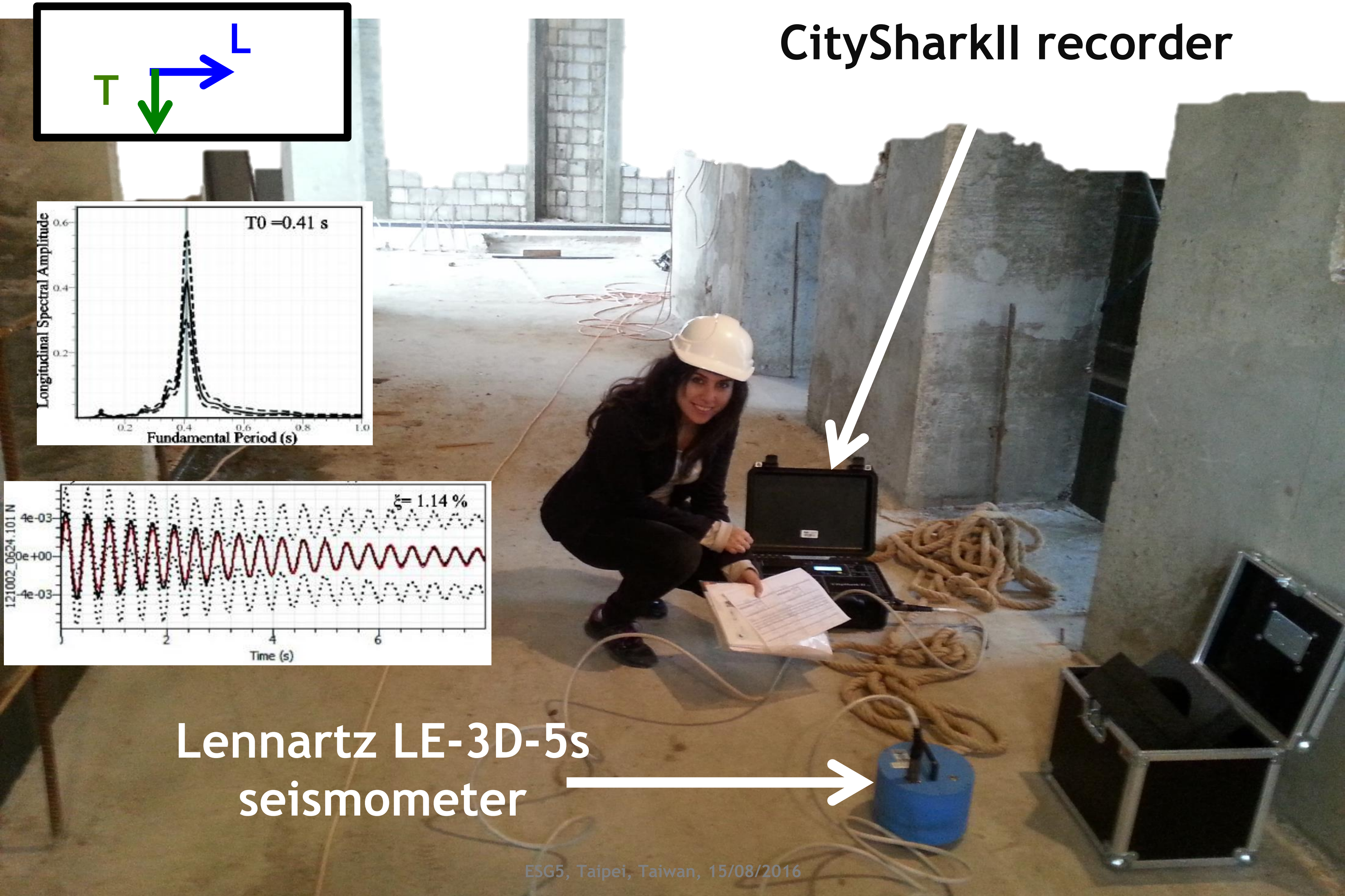
Sense-check : example application to Beirut City (Lebanon)

- Seismic hazard in Beirut / Lebanon
- Gathering of required data for Beirut City : ambient vibration measurements at ground level and in buildings
- Results


LEBANON
Seismicity of Lebanon
2006 – 2009
Focal depth (km)
Magnitudes
Md = 2
Md = 3
Md = 4
Md = 5
Md = 6
Serghaya
BEIRUT
Yammouneh
Roum
Rachaya
Dead Sea Transform Fault
AFRICAN
PLATE
ARABIAN
PLATE
43 Km
ESG5, Taipei, Taiwan, 15/08/2016



Needed :
Soil frequency
H/V amplitude
Building frequencies
PGA on rock
Building typology
Mediterranean Sea
f0 soil (Brax, 2013)
Beirut river
Ras Beirut
Manara
Borj Hammoud
Achrafieh
Mazraa
Furn el chebbak
El horch
Chyah
Jnah
H/V amplitude (Brax, 2013)
H/V Ground surfa
Buildings on rock
Buildings on soft site
Image © 2016 DigitalGlobe
Image © 2016 CNES / Astrium
3.72 km

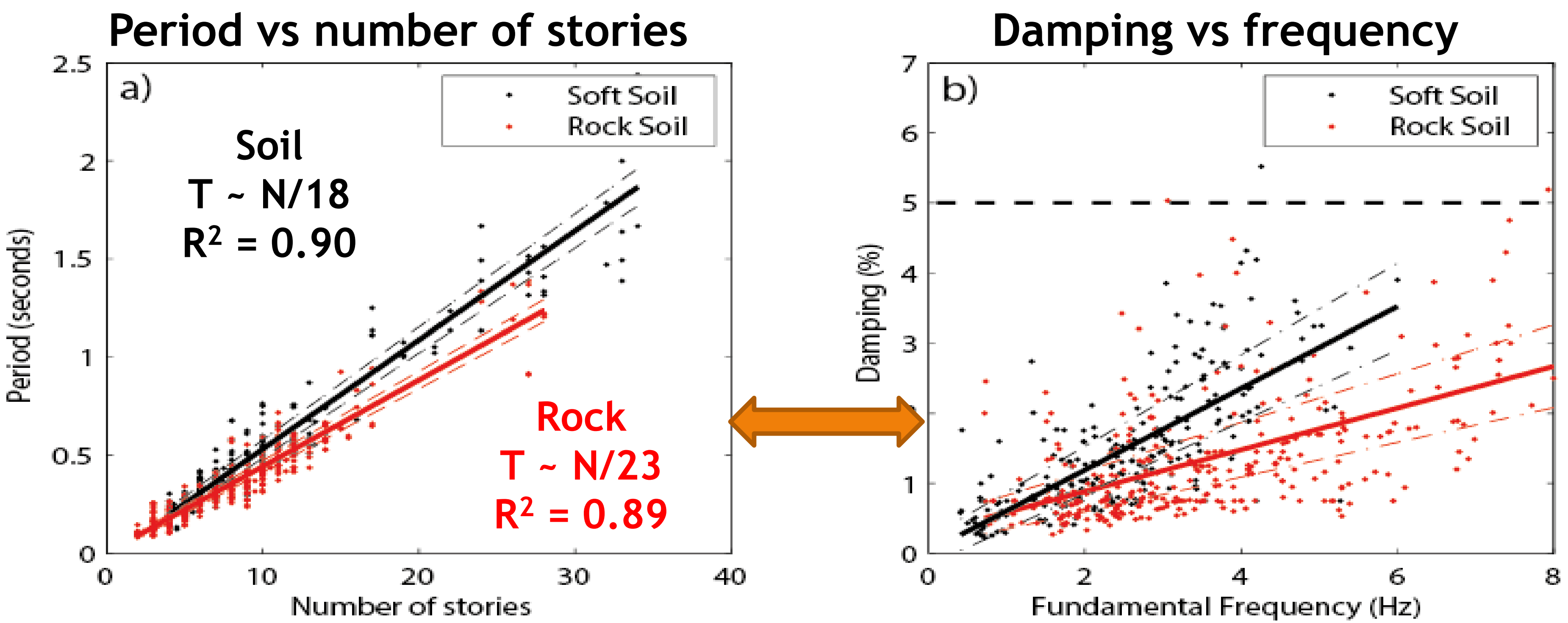

CitySharkII recorder
L
T
T0 =0.41 s
Longitudinal Spectral Amplitude
Fundamental Period (s)
ξ= 1.14 %
121002_0624.101 N
Time (s)
Lennartz LE-3D-5s
seismometer

Building set Description

330 buildings = 660 frequency and damping values

Rock Sites	"Soft" Sites
• 197 measurements • Typology: reinforced concrete frames • N= 1-26 floors • Age: 1910-2014	• 133 measurements • Typology: reinforced concrete frames • N= 1-33 floors • Age: 1910-2014

Determination of empirical formulae for Beirut buildings

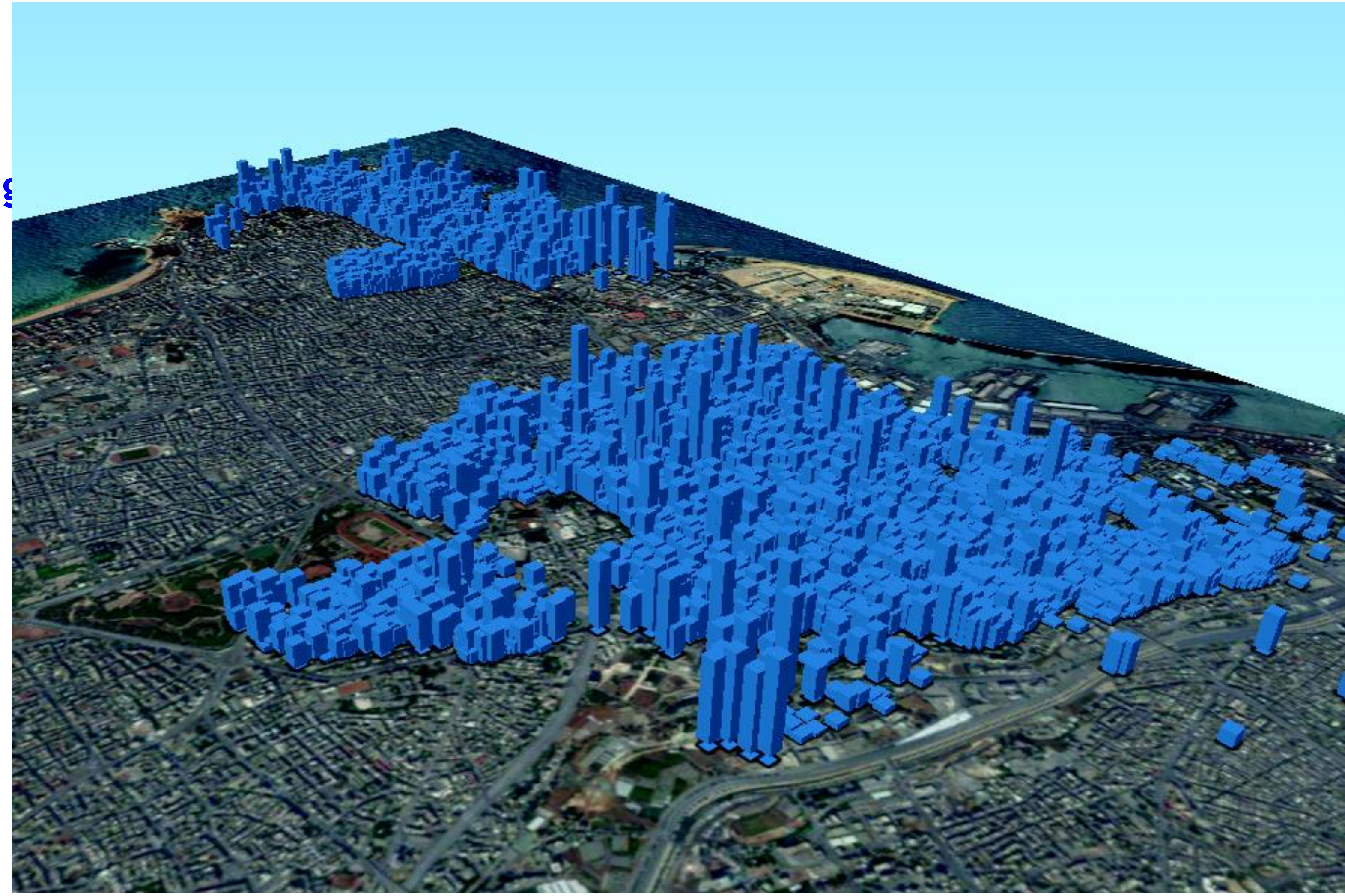


Longer periods on soils fully consistent with larger damping : indicative of some SSI (but with only slight frequency shifts)

Building inventory

Survey of 7362 buildings by members of Saint Joseph University (USJ) noting :

- the age of construction + material
- number of floors
- position of each building

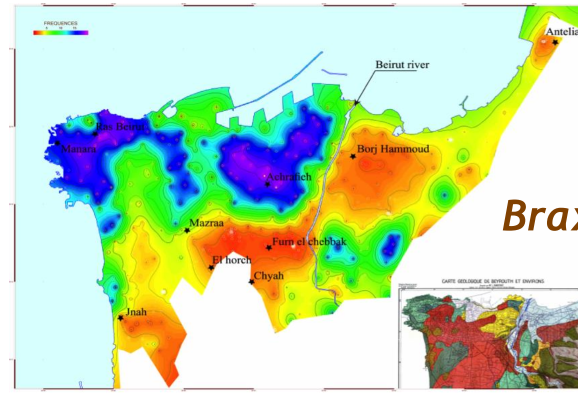


→ Assignment of a period for each building in the surveyed areas T_0=f(N, geology)

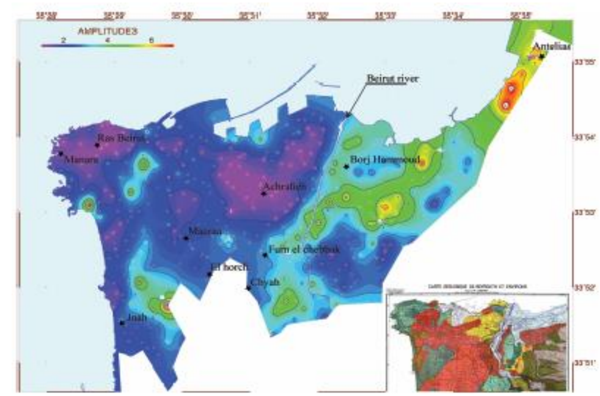
Integration

Typology class

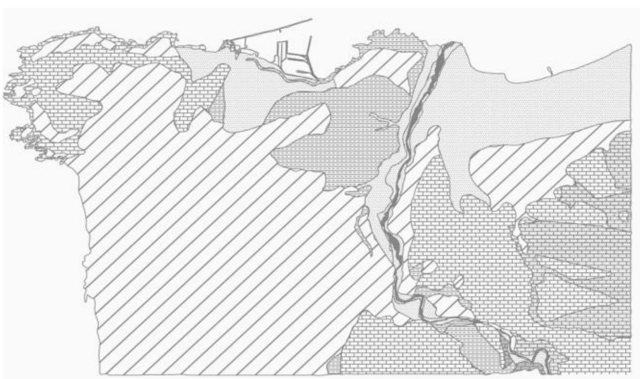
Class 1: Masonry	Class 2: Non-designed RC	Class 3: Low ductlity
• <1950 • N<4	• 1950-2005 • <1950 & N≥4	• >2005 (Lebanese seismic code introduction)

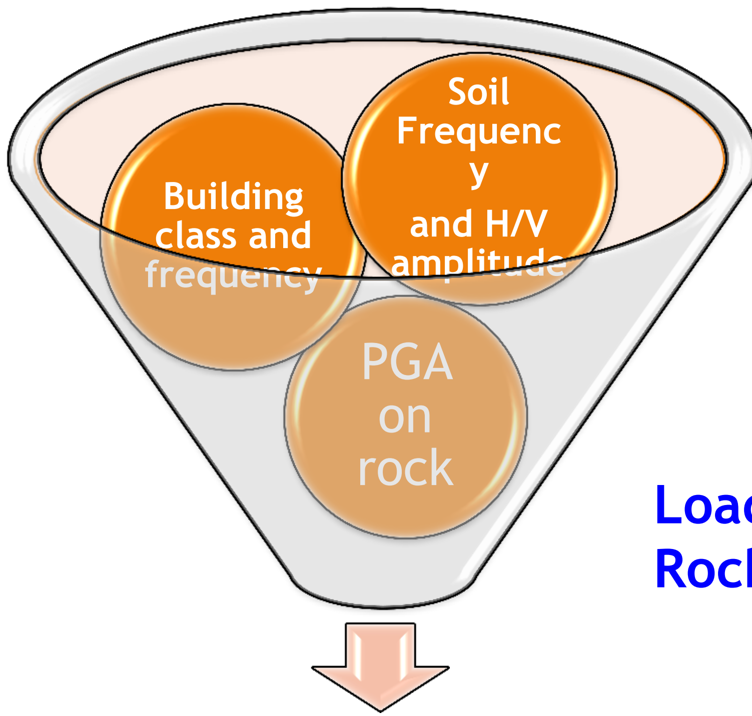


Brax 2013



Period:
T~N/23 rock sites
T~N/18 soft sites

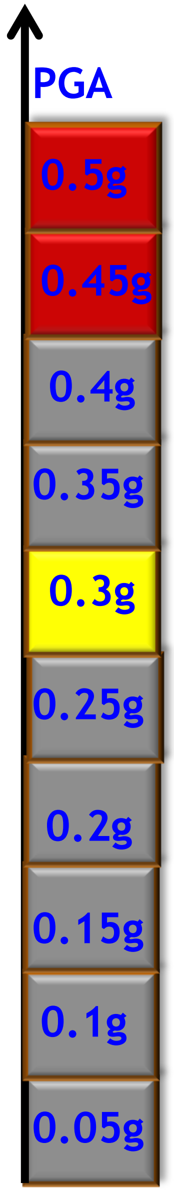


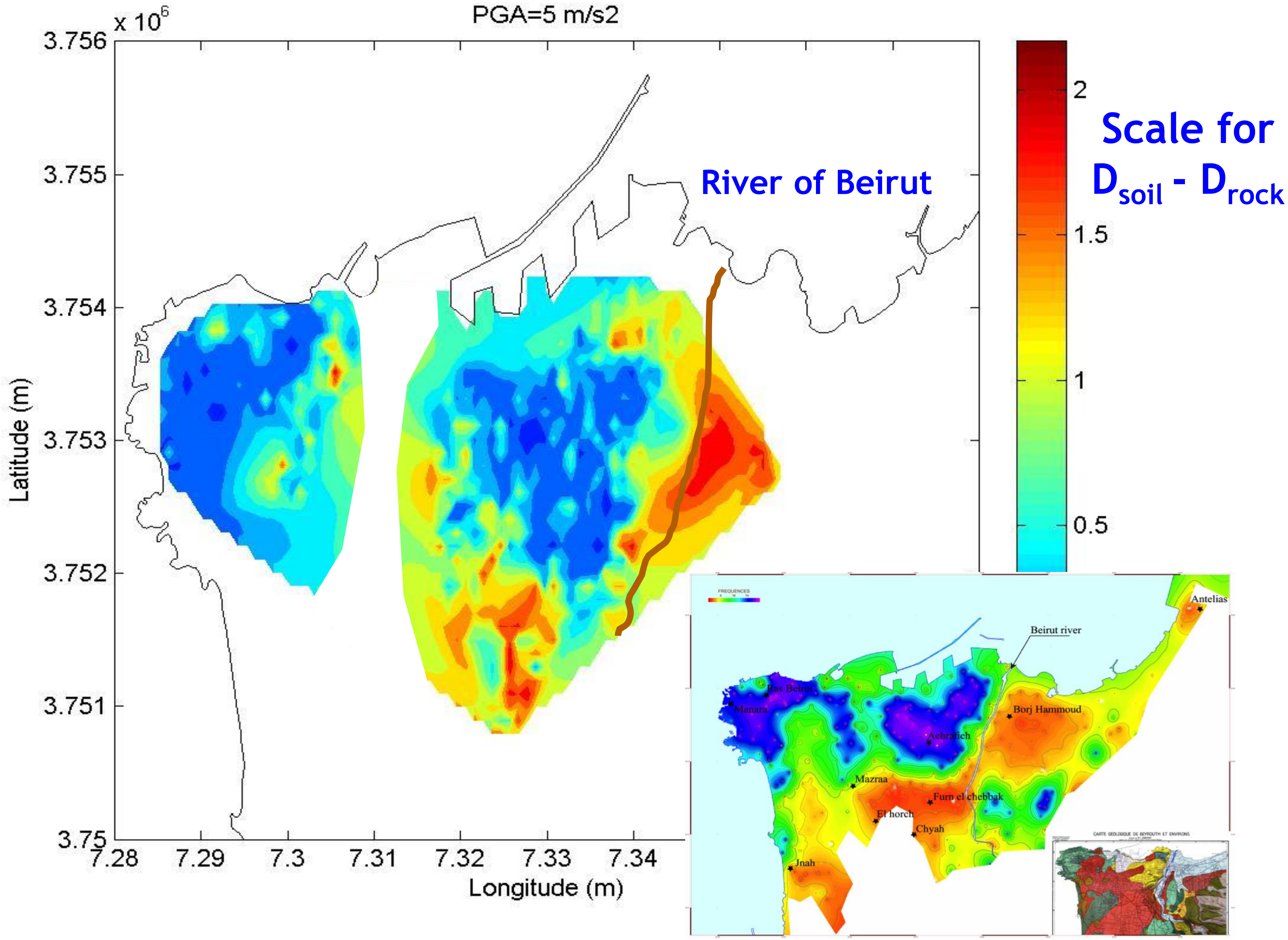


Loading scenarii :
Rock pga = 0.05g to 0.5g

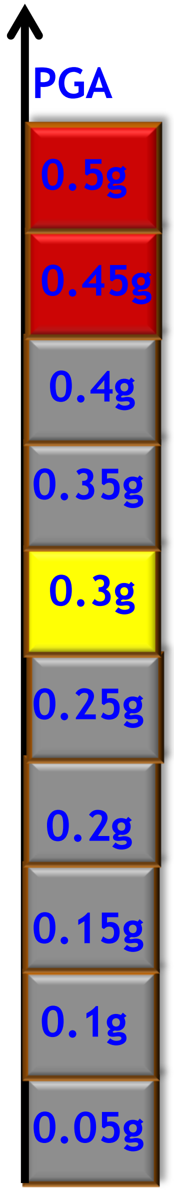
Damage increment

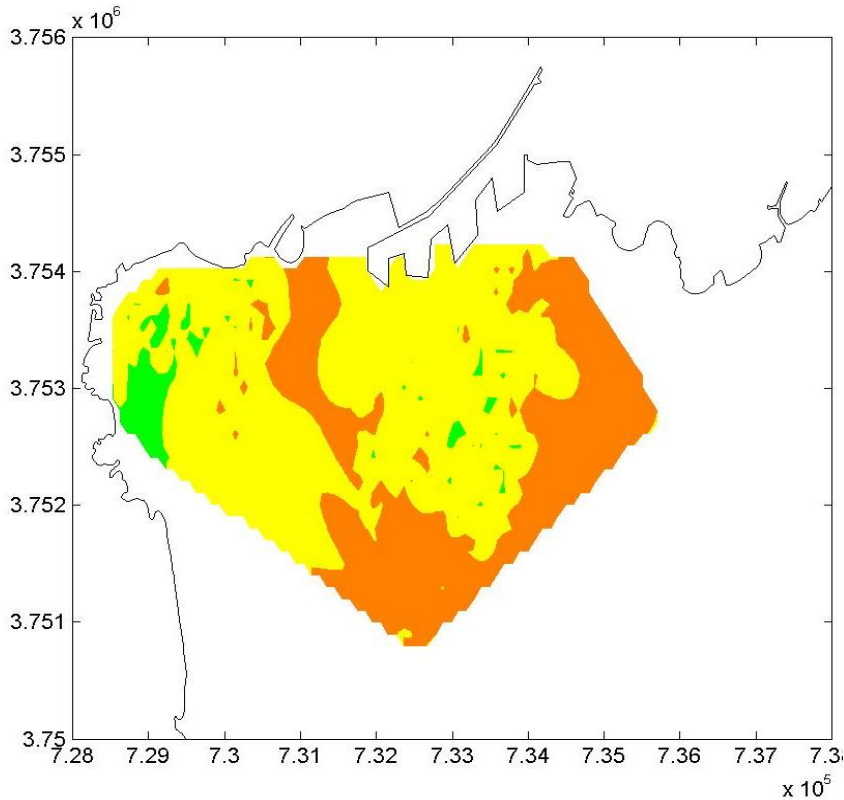
Damage increment maps of Beirut



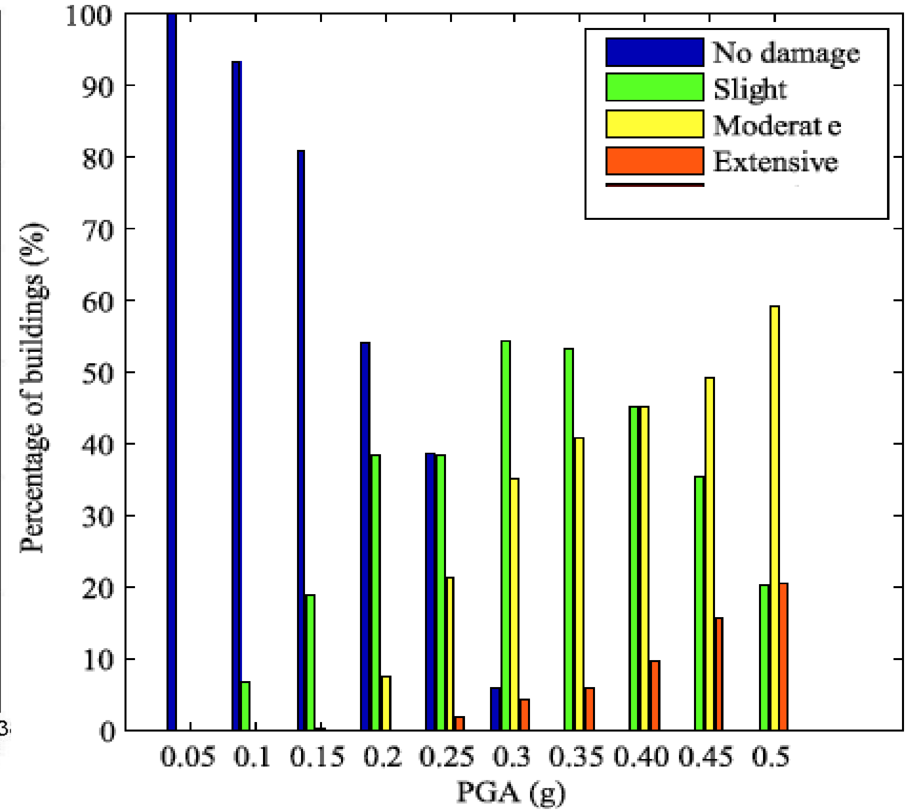


Absolute damage in Beirut City

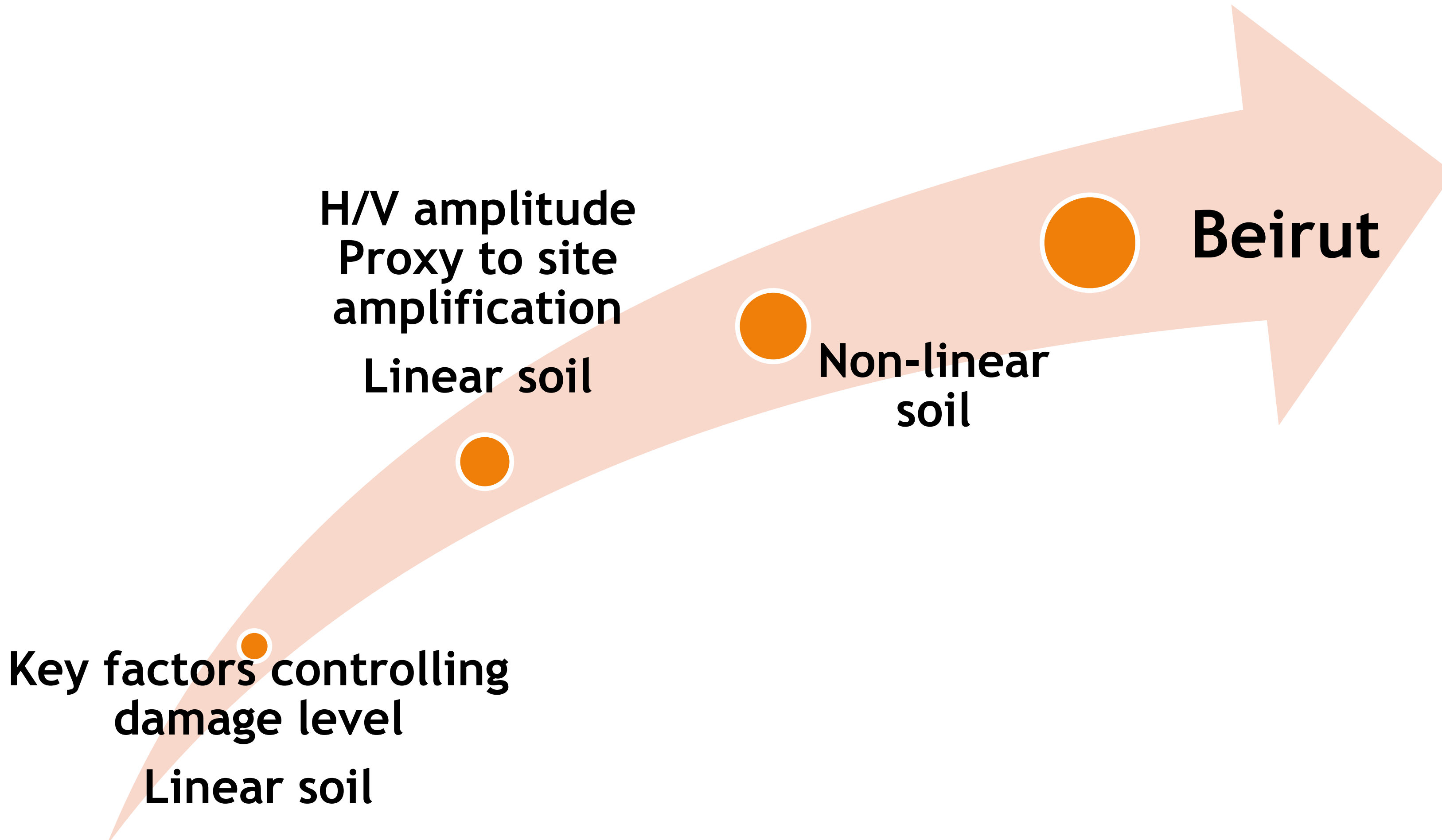




Evolution of damage level proportions with pga



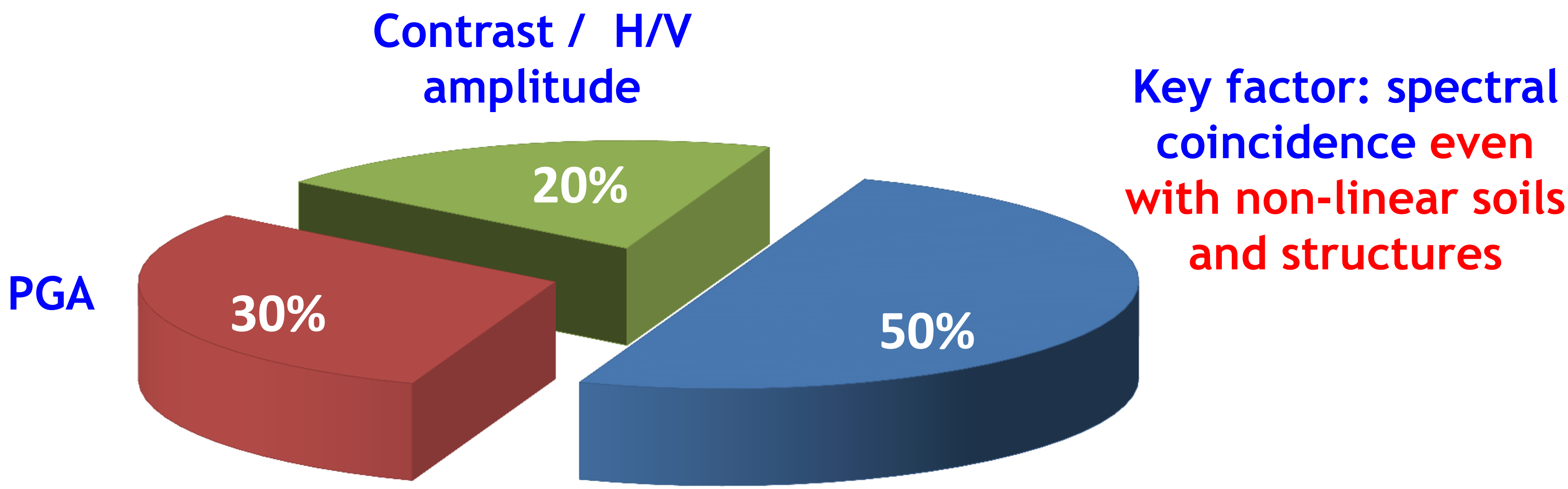
Summary



Key factors controlling damage level
Linear soil
H/V amplitude Proxy to site amplification
Linear soil
Non-linear soil
Beirut

Conclusions

1. Key parameters controlling the rock to soil damage increment



1. Easy implementation based on
   - Classical building inventory surveys
   - Extensive use of amnbient vinration measurements (ground level + building roofs)

Quite promising approach, but …
a few caveats and further steps

	Limitations	Perspectives
Input	Synthetic accelerograms	Real accelerograms (No real change on NL site response)
Site	Crude NGAW2 assumptions for NL site characteristics	More realistic NL behavior (Shallow NL underestimated, deep NL overestimated
Structure	Definition of damage index	? Other ?
	SDOF structures only	MDOF (some changes,mostly in the linear domain)
	Oversimplified elastoplastic model	More realistic structural NL models (Takeda, …)
ANN model	Neural networks : only 3 "basic parameters"	Other, or additional input parameters (loading : PGA → spectral shape, ??...)

+ testing in areas recently hit by damaging earthquakes (ex.: Puerto Viejo, Ecuador)

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