

Progetti Speciali ReLUIS 2014

 POLITECNICO DI MILANO



RS2 – Simulazioni di Terremoti ed Effetti Near-Source

Coordinatore Prof. Roberto Paolucci
Politecnico di Milano



Kick-off meeting
Department of Physics - University of Napoli, Monte Sant'Angelo
Napoli, March 27, 2014



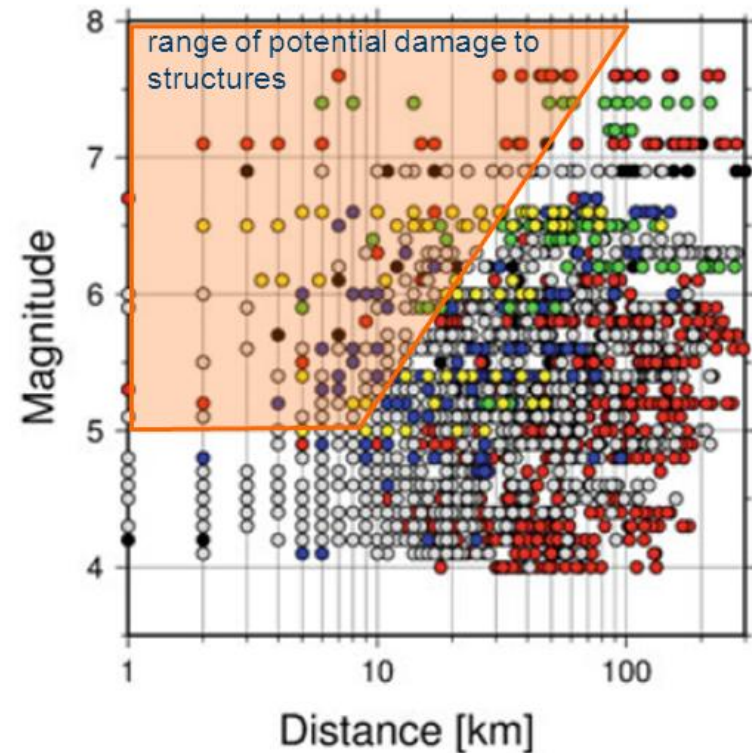
Unità di Ricerca	Responsabile	Budget (k€) 2014
Politecnico di Milano	Roberto Paolucci	25
Università di Napoli	Gaetano Festa	15
Università di Pavia	Carlo Lai	10
INGV Milano	Francesca Pacor	10
		60

Data di decorrenza: 1 febbraio 2014

Competenza temporale delle attività: 1 febbraio – 31 dicembre 2014



- ✓ moto sismico nel near-source scarsamente documentato da dati accelerometrici che coprono la varietà di condizioni di sito, sorgente, direttività, etc
- ✓ rarissimi i casi in cui si abbiano a disposizione dati near-source da reti accelerometriche dense per vincolare la variabilità spaziale del moto
- ✓ strumenti di simulazione numerica ormai ben collaudati, ma con limiti computazionali da risolvere (alta frequenza, non linearità)
- ✓ "sdoganare" gli accelerogrammi sintetici come efficace alternativa agli accelerogrammi reali per applicazioni ingegneristiche





- 1) affinare gli **strumenti di calcolo di accelerogrammi sintetici in condizioni near-source**, sia con approcci deterministici che stocastici, validandoli sulla base delle osservazioni dai terremoti dell'Aquila (in continuità con quanto sviluppato in RS2 del progetto 2010-2013) e dell'Emilia, e mostrandone le potenziali applicazioni in analisi di rischio sismico a scala territoriale;
- 2) produrre una **base di dati accelerometrici reali, pienamente caratterizzata in termini di meta-dati per gli effetti near-source** (componenti normali e parallele alla faglia, diverse metriche di distanza, condizioni di direttività, condizioni di sito), **associandola, nel corso del progetto, anche ad accelerogrammi sintetici**, a coprire in particolare quelle condizioni non ancora ben documentate dai dati reali;
- 3) elaborare i dati a disposizione per fornire **strumenti predittivi del moto sismico specifici per condizioni near-source**, per quanto riguarda in particolare le forme spettrali e la loro dipendenza dalle caratteristiche della faglia (componenti normali vs parallele, periodi dominanti del moto impulsivo, componenti verticali vs orizzontali, velocità e spostamento di picco, fattori di amplificazione sismica di sito in condizioni near-source);



- 4) studiare, sulla base dei risultati delle simulazioni numeriche e/o dei dati disponibili da reti accelerometriche dense, la **coerenza spaziale del moto sismico in condizioni near-source**;
- 5) valutare le potenzialità d'uso degli accelerogrammi sintetici da simulazioni numeriche, sia in termini di **risposta sismica di strutture estese** (ponti, condotte interrato), sia in termini di **analisi di stabilità di pendii**, validando i risultati con approcci più tradizionali di definizione dell'input sismico;
- 6) tradurre i risultati del progetto in **indicazioni normative o pre-normative**, in particolare per quanto riguarda gli effetti near-source su: (i) forme degli spettri elastici di progetto; (ii) fattori correttivi per gli effetti di sito; (iii) formule aggiornate per il calcolo di velocità e spostamento di picco in funzione delle ordinate spettrali di medio periodo; (iv) componenti verticali del moto e rapporto V/H.
- 7) sviluppare documenti pre-normativi per l'inclusione degli **effetti near-source negli scenari di progetto per le costruzioni**.

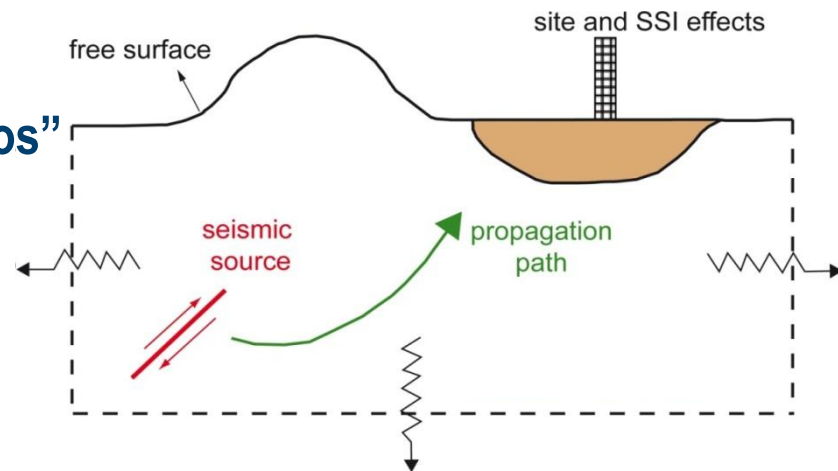


Objective (Dream?)

To simulate “physics-based earthquake scenarios”

as realistic as possible in terms of:

- ✓ the complexity of the seismic source
- ✓ the complexity of the geological and morphological environment
- ✓ the frequency range of the seismic excitation and of resulting ground motion





The Spectral Element Code SPEED

<http://mox.polimi.it/it/progetti/speed/SPEED/Home.html>



DIPARTIMENTO DI INGEGNERIA CIVILE E AMBIENTALE



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SPEED SPectral Elements in Elastodynamics with Discontinuous Galerkin

SPEED is an open-source code for the simulation of seismic wave propagation in three-dimensional complex media.

SPEED is jointly developed by MOX (The Laboratory for Modeling and Scientific Computing) of the Department of Mathematics and Department of Civil and Environmental Engineering (DICA) at Politecnico di Milano.

SPEED is a discontinuous Galerkin spectral element code that incorporates the open-source libraries METIS and MPI for the parallel computation (mesh partitioning and message passing). It has been designed with the aim of simulating large-scale seismic events, allowing the evaluation of the typically multi-scale wave propagation problems in its complexity, from far-field to near-field and from near-field to soil-structure interaction effects.

The main features of the code are:

- Naturally oriented to large scale applications;
- Native parallel implementation;
- Scalable approach: subdomain grids are generated independently with possibly variable granularity and spectral approximation degree;
- Externally created unstructured meshes (e.g.: CUBIT);
- Complex constitutive models including visco-elastic, visco-plastic and non-linear constitutive models;
- Handling the partitioning and load balancing of the computational domain by incorporating the METIS software library;
- Post-processing output in GID and VTK format



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SPEED SPectral Elements in Elastodynamics with Discontinuous Galerkin



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Chiara Smerzini
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Ambientale
Politecnico di Milano

Mazzieri I. et al. (2013) SPEED-Spectral Elements in Elastodynamics with Discontinuous Galerkin: a non-conforming approach for 3D multi-scale problems, Int. J. Num. Meth. Eng., 95 (12), DOI: 10.1002/nme.4532



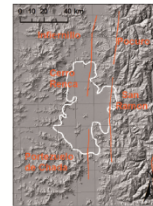
Flowchart for scenario simulations by SPEED

INPUT DATA

SRTM 90m Digital Elevation Model [Software: ArcGIS]

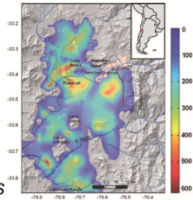


Regional seismotectonic context, identification of active faults



Geological and geotechnical characterization of city areas

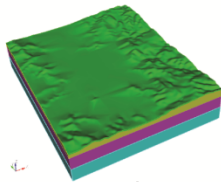
e.g. bedrock isobaths



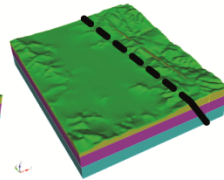
NUMERICAL MODEL

MESH DESIGN [Software: CUBIT, Rhino]

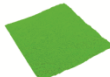
topography + crustal model



fault geometry



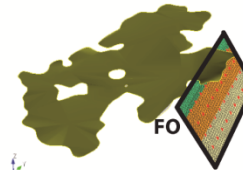
auxiliary triangular mesh



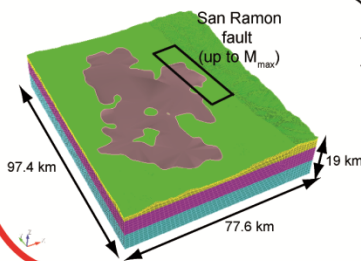
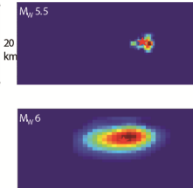
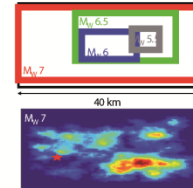
topography [XYZ.out] alluvial-bedrock interface [ALL.out]



GENERATION OF SCENARIO EQKS [Software: Matlab]



FO



Crustal model

Z (km)	ρ (t/m ³)	V_s (m/s)	V_p (m/s)	Q (-)
0-2.2	2.4	2400	4700	240
2.2-8.9	2.7	3200	5900	320
>8.9	2.8	3450	6200	350

Santiago Basin

$$V_s(z) = 400 + 55\sqrt{z}$$

$$V_p(z) = 1730 + 60\sqrt{z}$$

$$\rho(z) = 2100 + 0.15z$$

$$Q_s = 40$$

For a given fault (M_{max}), the eqk scenario is defined by:

- M_w
- position of rupture area w.r.t. Fault Origin (FO)
- slip distribution
- hypocenter location w.r.t. FO and focal depth
- rupture length and width (L, W)
- rake angle
- rupture velocity
- rise time



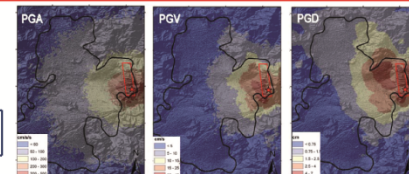
RUN SPEED

POST-PROCESS

BROADBAND GROUND SHAKING MAPS [Software: Matlab]

collection of results in a format compatible with GID/ArcGIS and MRQuake computations

Long (°E)	Lat (°N)	PGD (cm)	PGV (cm)	PGA (cm/s ²)	PSA 0.3s (cm/s ²)	PSA 1.0s (cm/s ²)	PSA 3.0s (cm/s ²)	PSA 5.0s (cm/s ²)
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Tools (suggested): CAD, Rhinoceros, ArcGIS

1.1) Identification of active faults (literature overview – geologic/seismic evidences):

- location;
- focal mechanism;
- size;
- Mmax.

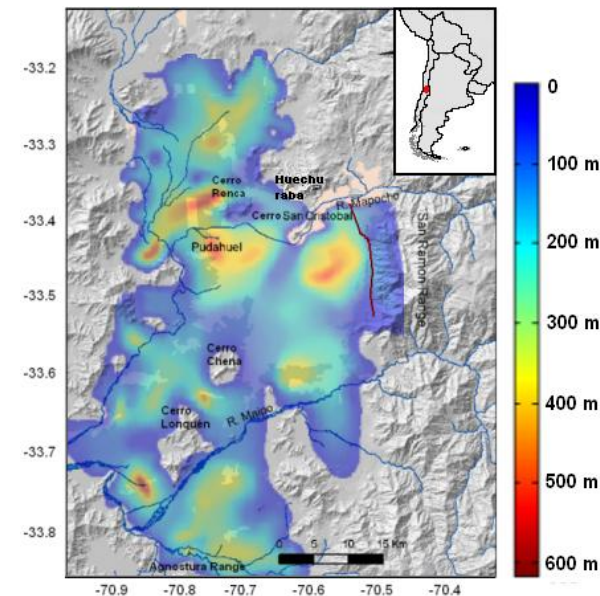
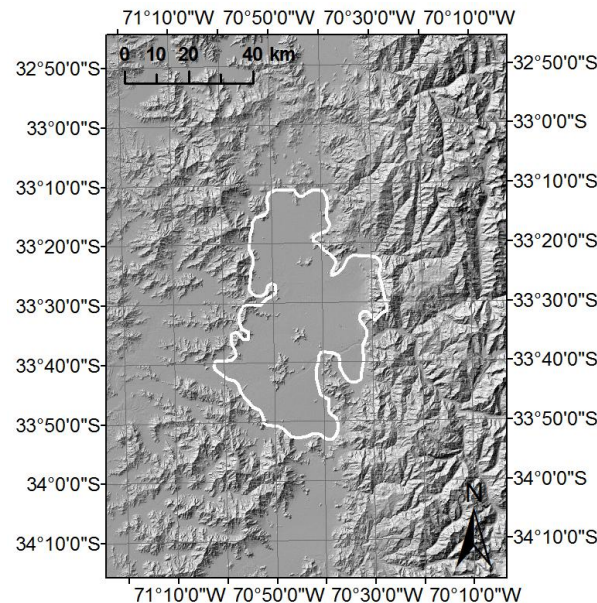
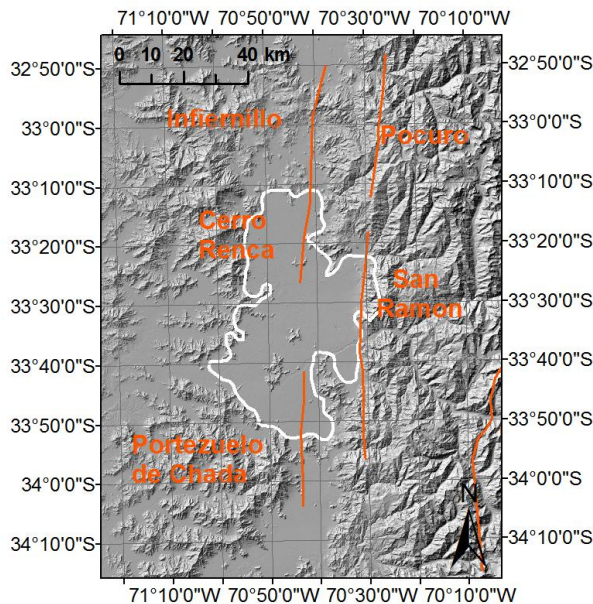
1.2) Digital Elevation Model (DEM): available at

<http://srtm.csi.cgiar.org/>

- 90m resolution

1.3) Geologic, geophysical and geotechnical model:

- 3D structure;
- velocity profiles;
- deep crustal model.





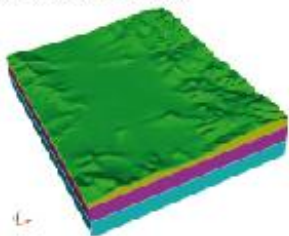
Tools (suggested): CUBIT

2.1) geometry and mesh design (1:3 refinement scheme for conforming model or non-conforming model)

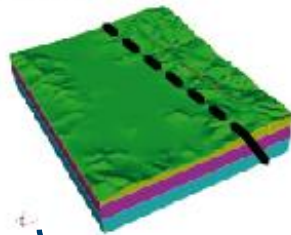
2.2) auxiliary (independent) mesh for “Not Honoring” Procedure

2.3) auxiliary (independent) mesh for kinematic finite fault model

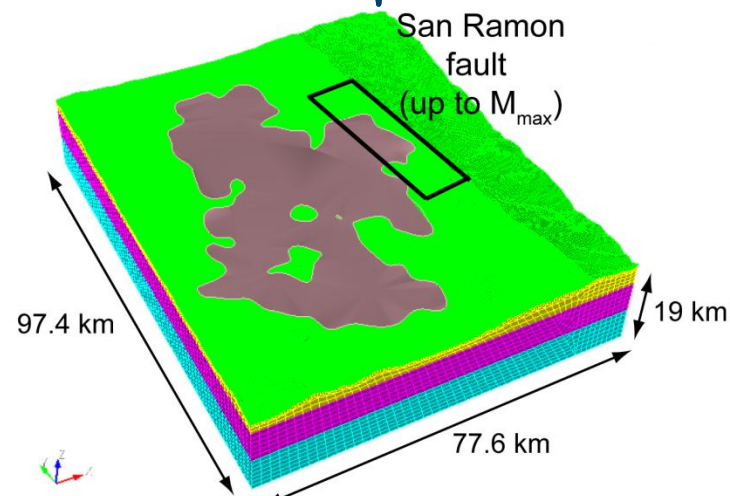
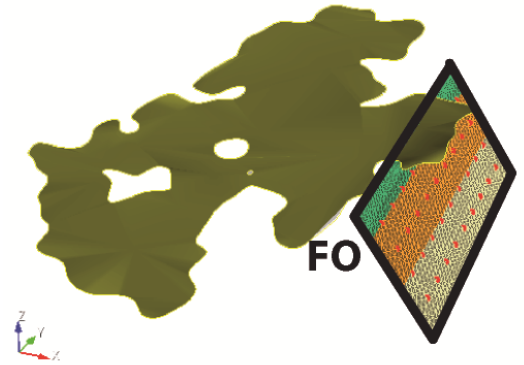
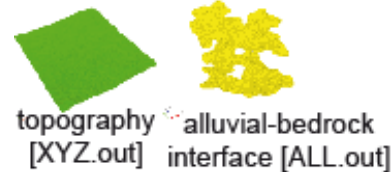
topography + crustal model



fault geometry



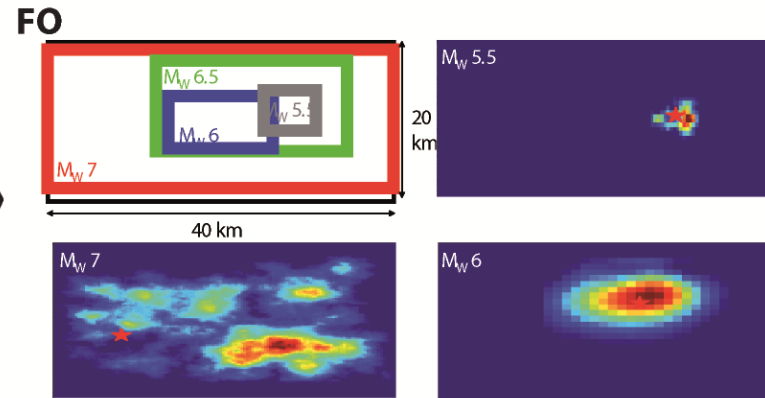
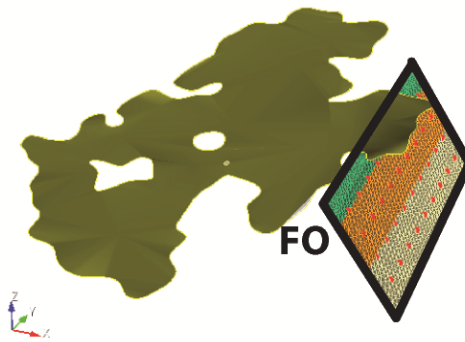
auxiliary triangular mesh



Step 3: source input creation

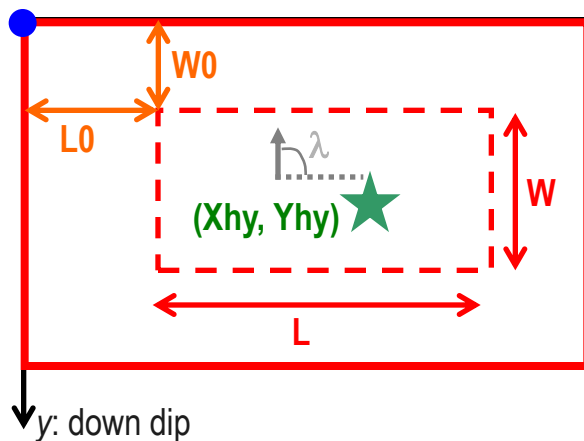
Tools: Matlab toolbox

Automatic generation of fault rupture scenarios breaking any arbitrary portion of the seismogenic structure/s implemented in the mesh (as in Step 1)



Fault Origin (FO)

x: along strike



For a given fault (M_{max}), define:

- Moment magnitude: M_W (M_0)
- position of rupture area w.r.t. FO: L_0 , W_0
- slip distribution $s(x,y)$ (SRCMOD database included: <http://www.seismo.ethz.ch/srcmod/>)
- hypocenter location w.r.t. FO and focal depth: X_{hy} , Y_{hy} , D
- rupture length and width: L , W
- rake angle (λ), rupture velocity (V_R), rise time (τ)

Step 3: source input creation

Features for seismic input

Kinematic modeling of an extended seismic source

$$m_{ij}^k(\underline{x}, t) = \frac{M_0^k(\underline{x}, t)}{V^k} \left(v_i^k n_j + v_j^k n_i \right)$$

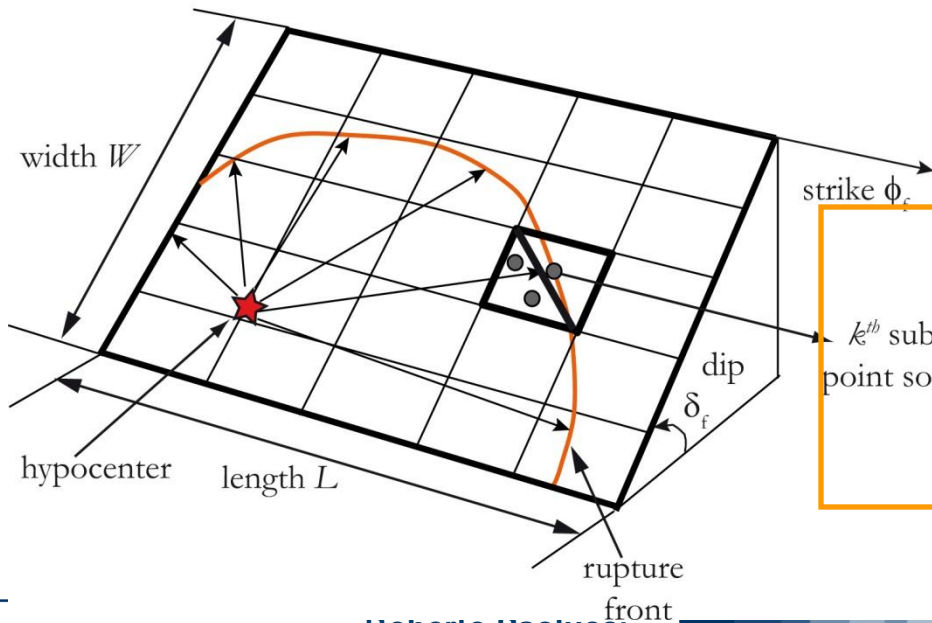
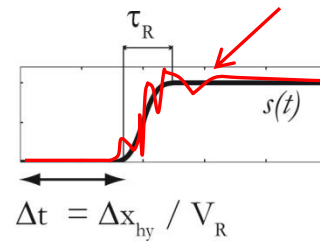
volume of the k^{th} subfault slip and normal fault vectors $f(\delta_f, \lambda_f, \phi_f)$

$$M_0^k(\underline{x}, t) = \mu^k \Delta u^k A^k s(t - \Delta t^k; \tau_R^k)$$

shear modulus co-seismic slip area Slip source function

How to introduce high-frequency components?

How to introduce spatial incoherency?



- shear modulus μ^k
 - slip Δu^k
 - area A^k
 - rise time τ_R^k
 - rupture velocity V_R^k
 - rake angle λ_f^k
 - delay Δt^k
- k^{th} subfault point source x_s^n

Expected times required to compute a typical scenario simulation

INPUT DATA

SRTM 90m Digital Elevation Model [Software: ArcGIS]

Regional seismotectonic context, identification of active faults

Geological and geotechnical characterization of city areas
e.g. bedrock isobaths

NUMERICAL MODEL

MESH DESIGN [Software: CUBIT, Rhino]

topography + crustal model, fault geometry, auxiliary triangular mesh

GENERATION OF SCENARIO EQKS [Software: Matlab]

topography [XYZ.out], alluvial-bedrock interface [ALL.out]

San Ramon fault (up to M_{max})

Crustal model					
Z (km)	ρ (t/m ³)	V_p (m/s)	V_s (m/s)	Q_p (-)	Q_s (-)
0-2.2	2.4	2400	4700	240	240
2.2-8.9	2.7	3200	5900	320	320
>8.9	2.8	3450	6200	6200	350

Santiago Basin

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$$V_p(z) = 1730 + 60\sqrt{z}$$

$$\rho(z) = 2100 + 0.15z$$

$$Q_s = 40$$

For a given fault (M_{max}), the eqk scenario is defined by:

- M_W
- position of rupture area w.r.t. Fault Origin (FO)
- slip distribution
- hypocenter location w.r.t. FO and focal depth
- rupture length and width (L, W)
- rake angle
- rupture velocity
- rise time

INPUT DATA + MESH:
 ~ 5 days (if input data – particularly the 3D soil model - are easily available and given in a suitable format)

RUN SPEED

RUN (SUPER-COMPUTER):
 ~ 4-5 hours for tens of million nodes (512 MPI, FERMI)

POST-PROCESS

BROADBAND GROUND SHAKING MAPS [Software: Matlab]

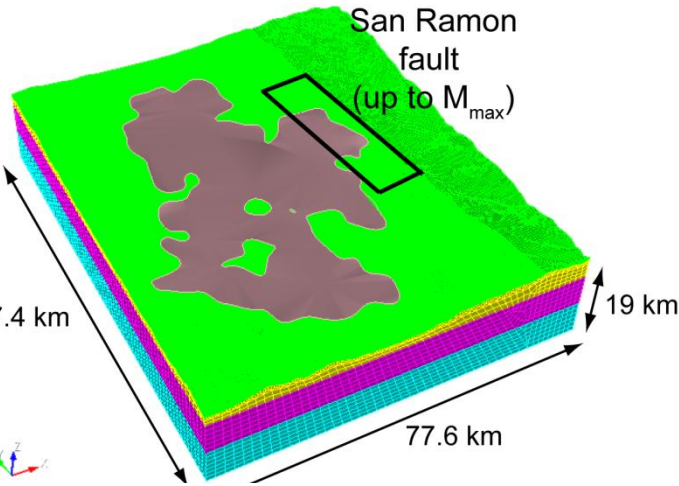
collection of results in a format compatible with GID/ArcGIS and MRQuake computations

Long (°E)	Lat (°N)	PGD (cm)	PGV (cm)	PGA (cm/s ²)	PSA 0.3s (cm/s ²)	PSA 1.0s (cm/s ²)	PSA 3.0s (cm/s ²)	PSA 5.0s (cm/s ²)
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~ 2 hours on a standard laptop – 4 labs (CPU @ 2.8 GHz, RAM 8 Gb)



SANTIAGO DEL CILE



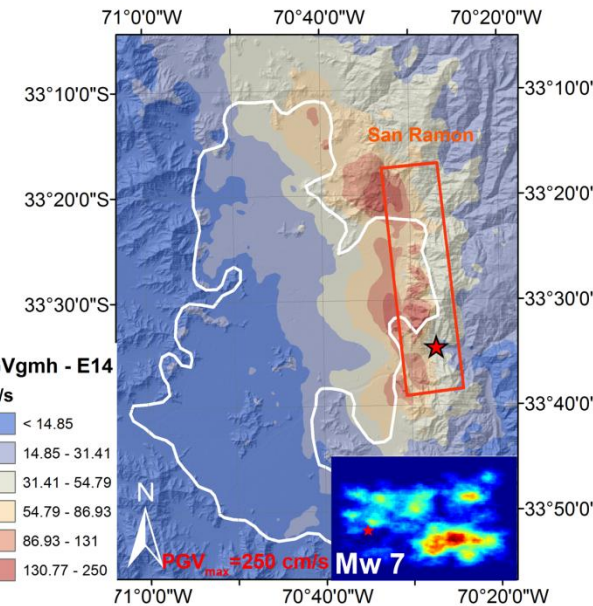
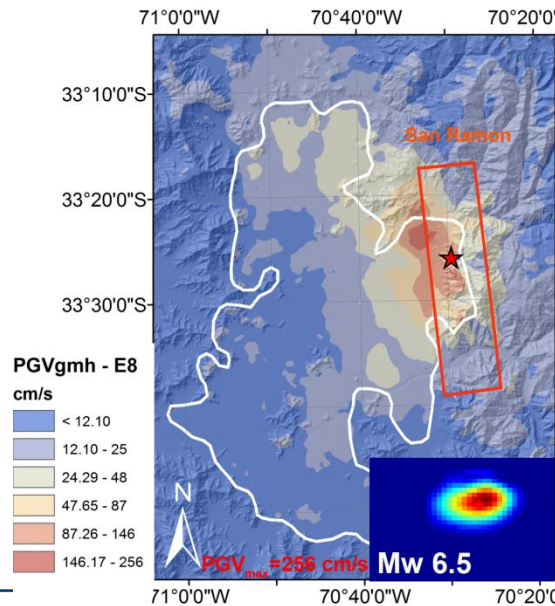
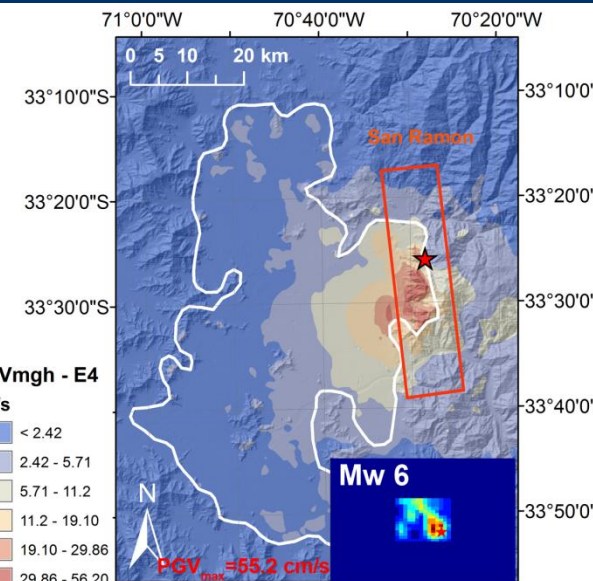
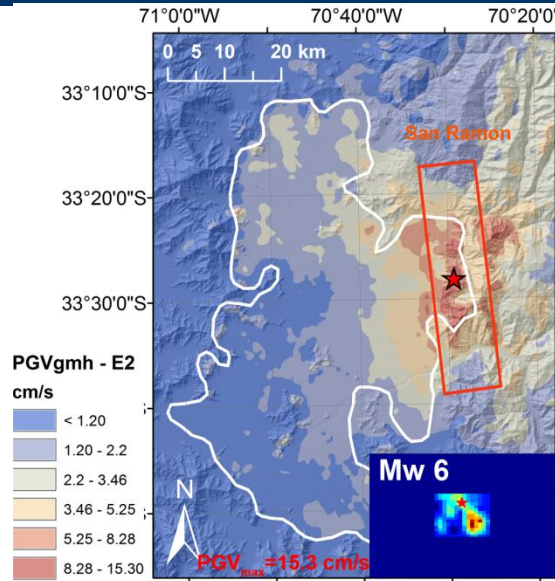
Crustal model

Z (km)	ρ (t/m ³)	V_S (m/s)	V_P (m/s)	Q (-)
0-2.2	2.4	2400	4700	240
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Santiago Basin

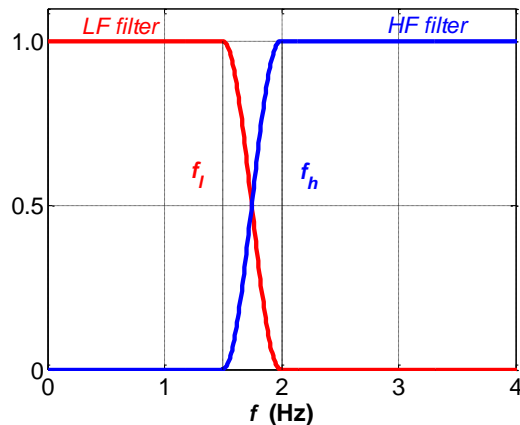
$$\left\{ \begin{array}{l} V_S(z) = 400 + 55\sqrt{z} \\ V_P(z) = 1730 + 60\sqrt{z} \\ \rho(z) = 2100 + 0.15z \\ Q_S = 40 \end{array} \right.$$

~ 5 hours on FERMI using 512 cores

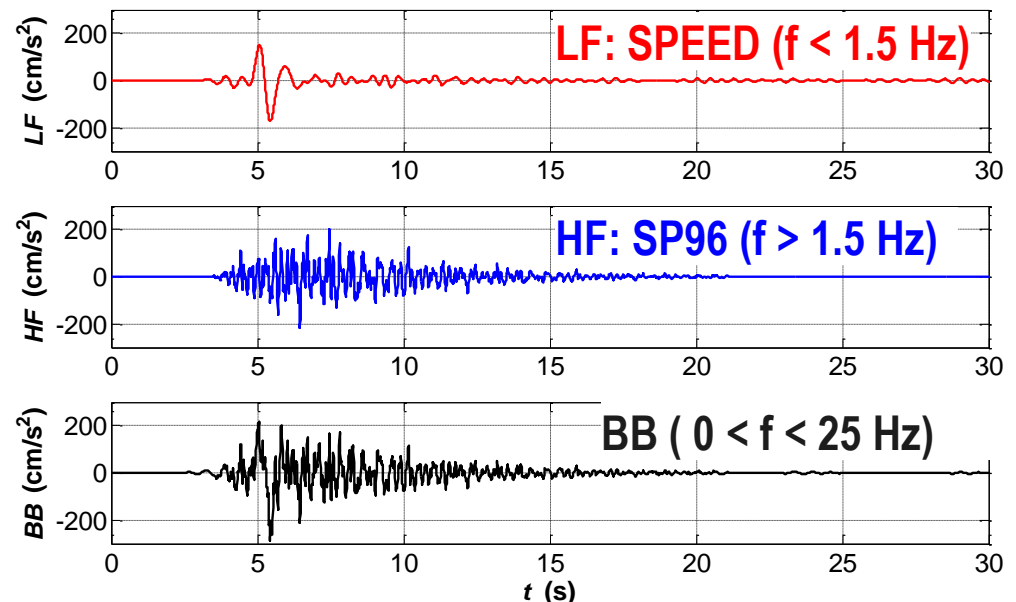
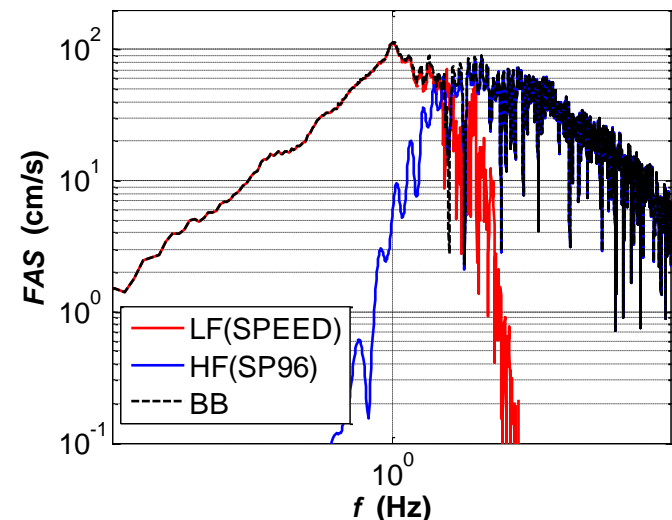




Hybrid method, embedded in the post-processing toolbox, to generate **broadband ground motion shaking maps** usable over a wide range of periods for engineering aims



Physics-based waveforms provided by **SPEED at LF ($f < f_i$)** are combined with the synthetic accelerograms computed through the stochastic approach of Sabetta & Pugliese (1996, **SP96**) at **High Frequency ($f > f_h$)**, by using matching filters

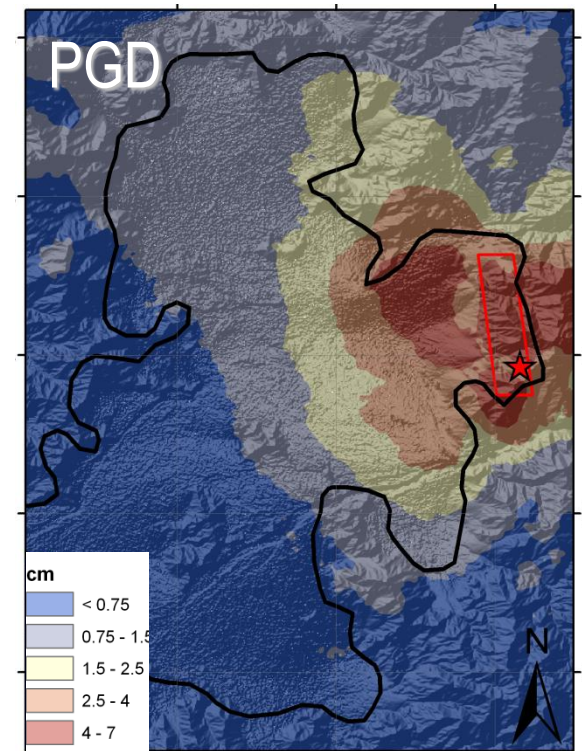
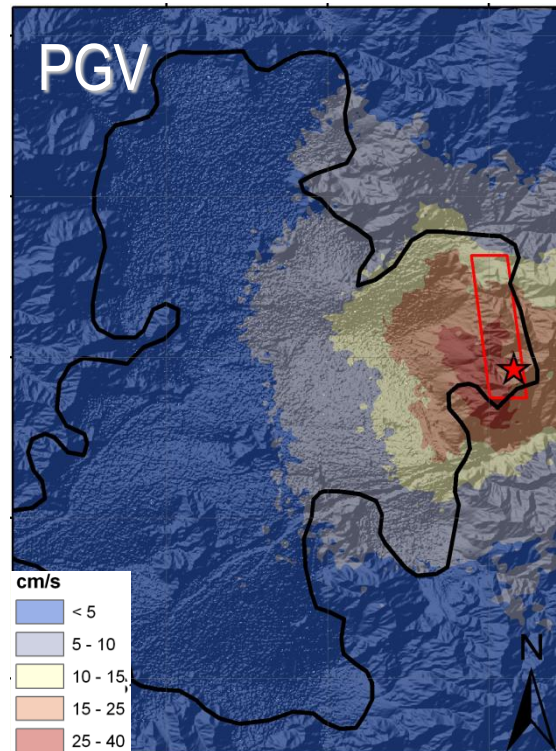
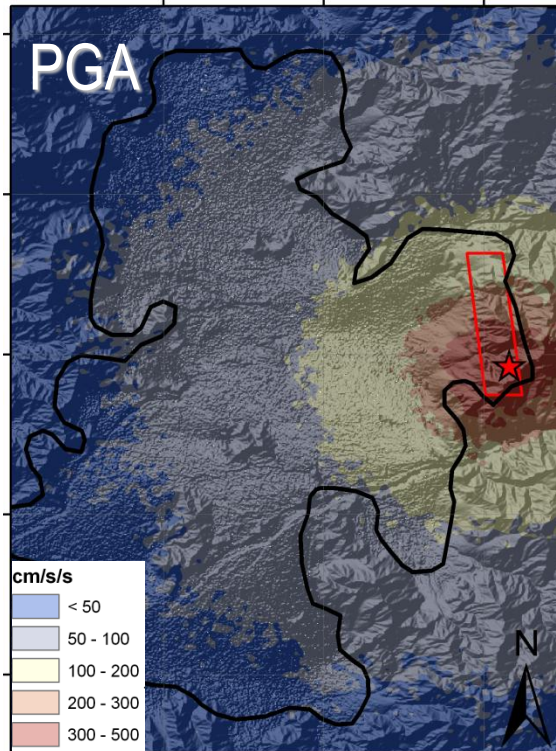


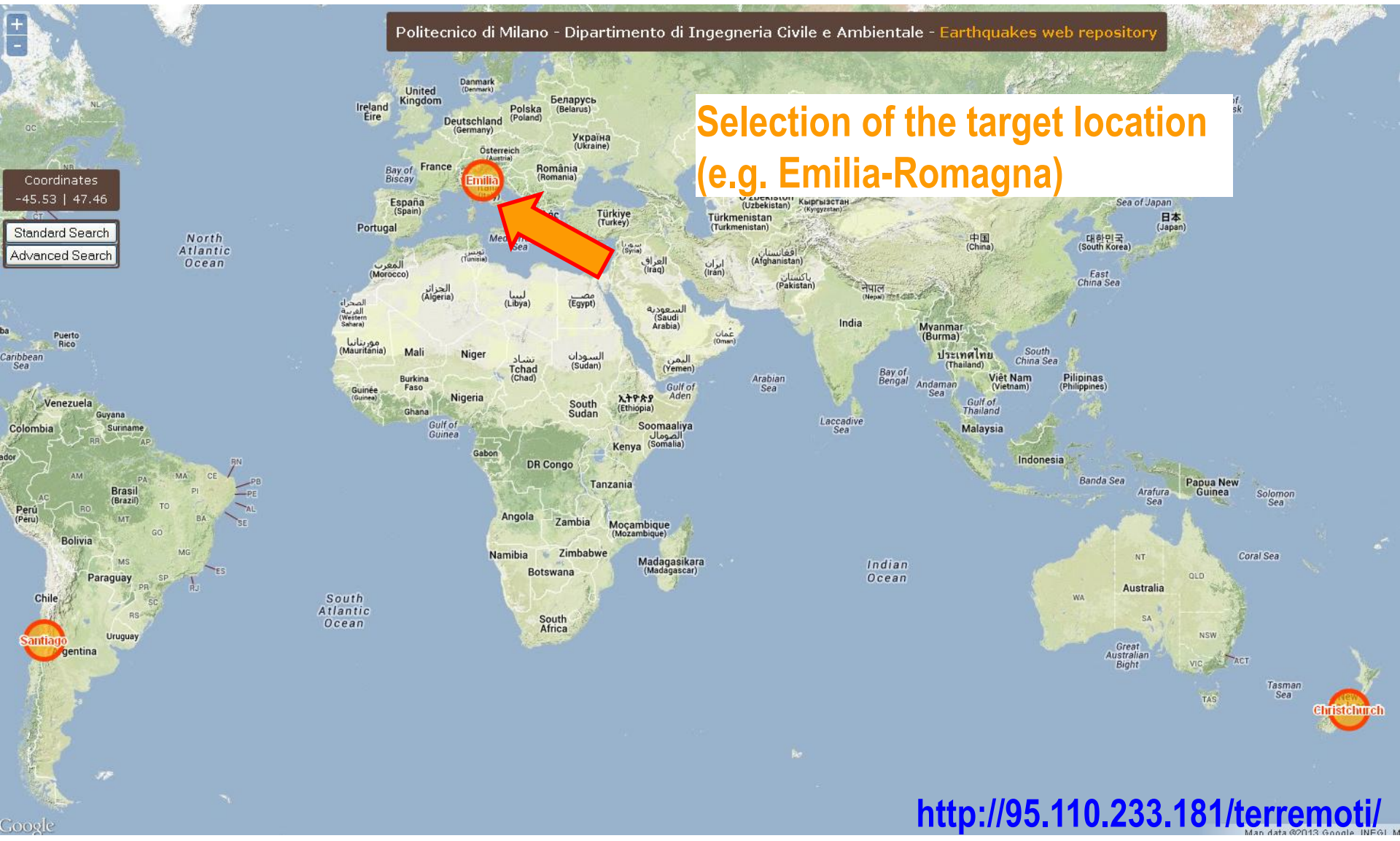


GROUND SHAKING MAPS: results are collected on a regular (~ 600 m) of observation points at ground surface and saved in the following format:

Long (E)	Lat (N)	PGD (cm)	PGV (cm)	PGA (cm/s/s)	PSA 0.3s (cm/s/s)	PSA 1.0s (cm/s/s)	PSA 3.0s (cm/s/s)	PSA 5.0s (cm/s/s)
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For each ground motion parameter, the geometric mean of horizontal component is provided



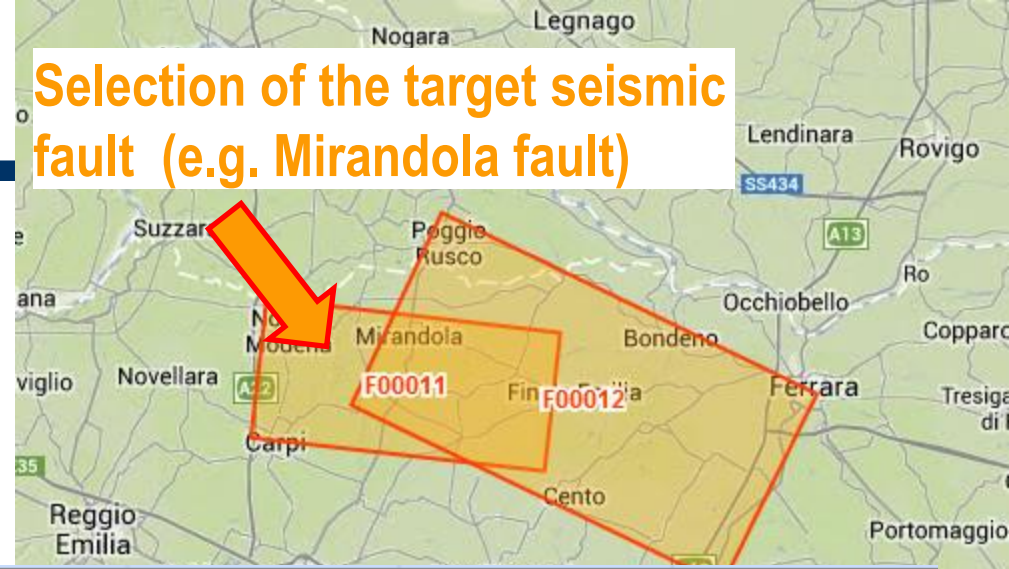


<http://95.110.233.181/terremoti/>



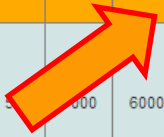
Web repository of seismic scenarios

Selection of the target seismic fault (e.g. Mirandola fault)



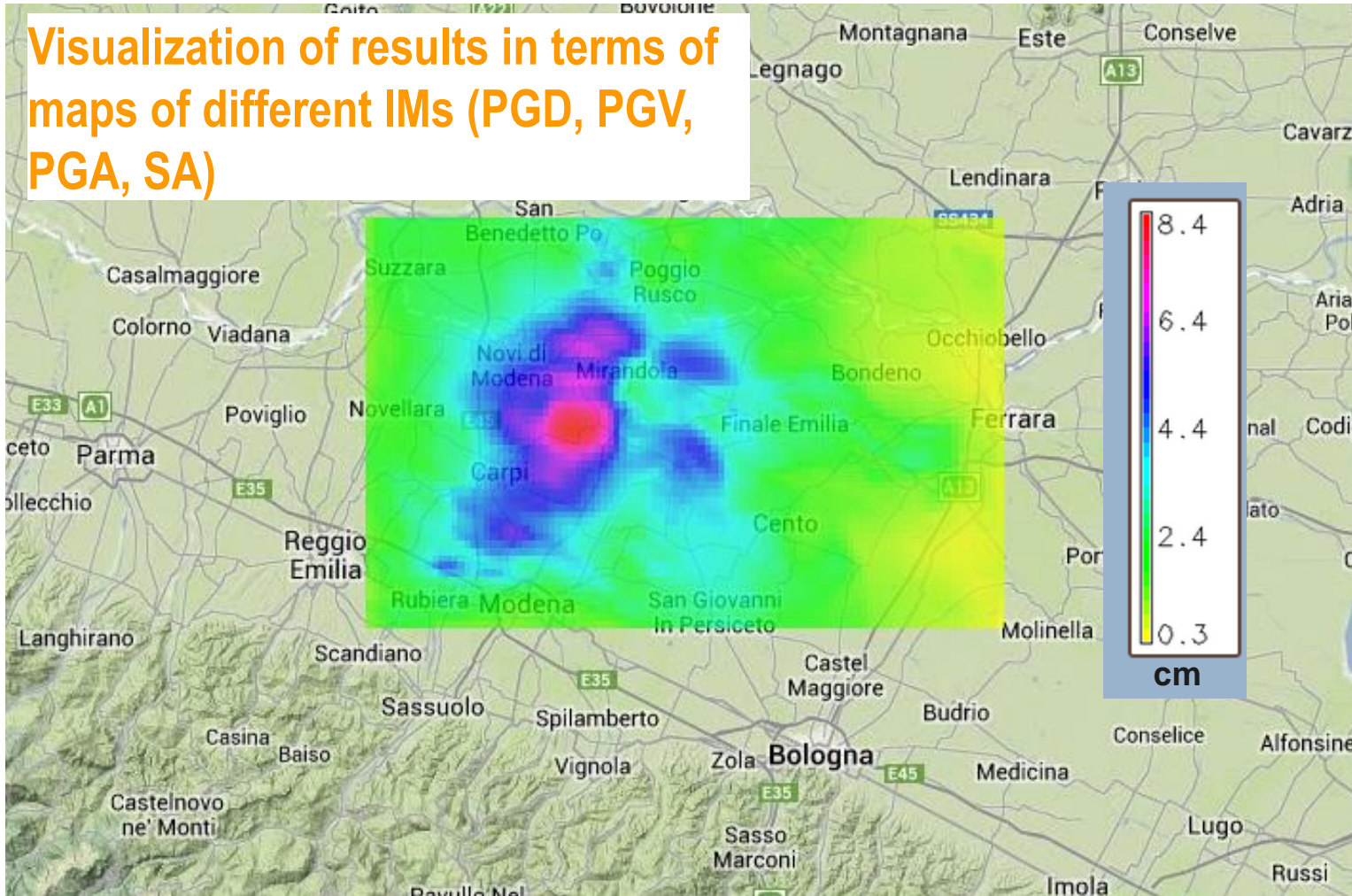
SLIP ORIGIN	SCENARIO ID	MW	L [KM]	W [KM]	HYP0 LAT [DEGREES]	HYP0 LON [DEGREES]	HYP0 DEPTH [KM]	RAKE ANGLE [DEGREES]	RUPTURE VELOCITY [KM/S]	RISE TIME [S]	BROADBAND	SCENARIO PARAMETERS	SCENARIO FILE	RASTER
	E00101	6	32000	20000	44.851	11.086	-10200	90	2800	0.7	False	Download File param	Download File scen	PGD VIEW MAP
	E00103	5.5	6000	6000	44.822588	11.094198	-12771.1513	90	2500	0.6	False	Download File param	Download File scen	PGD VIEW MAP
	E00105	5.5	6000	5000	44.862875	10.937637	-10200.0009	90	2500	0.6	False	Download File param	Download File scen	PGD VIEW MAP
	E00106	6	12000	7000	44.85323	11.058344	-10200.0009	100	2800	0.7	False	Download File param	Download File scen	PGD VIEW MAP

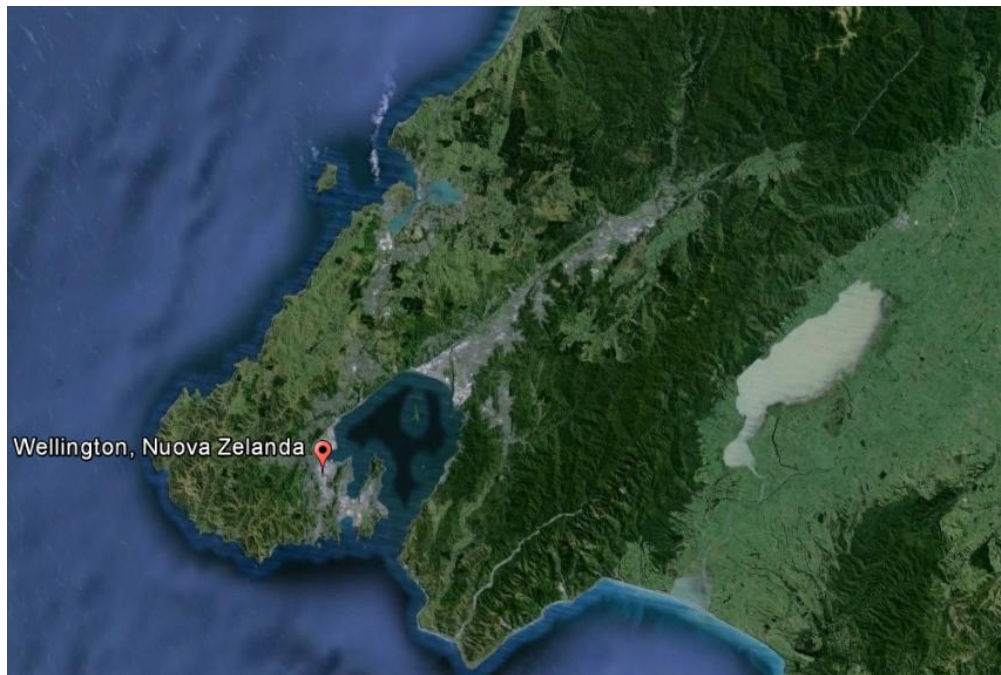
Selection of the target rupture scenario





Visualization of results in terms of maps of different IMs (PGD, PGV, PGA, SA)



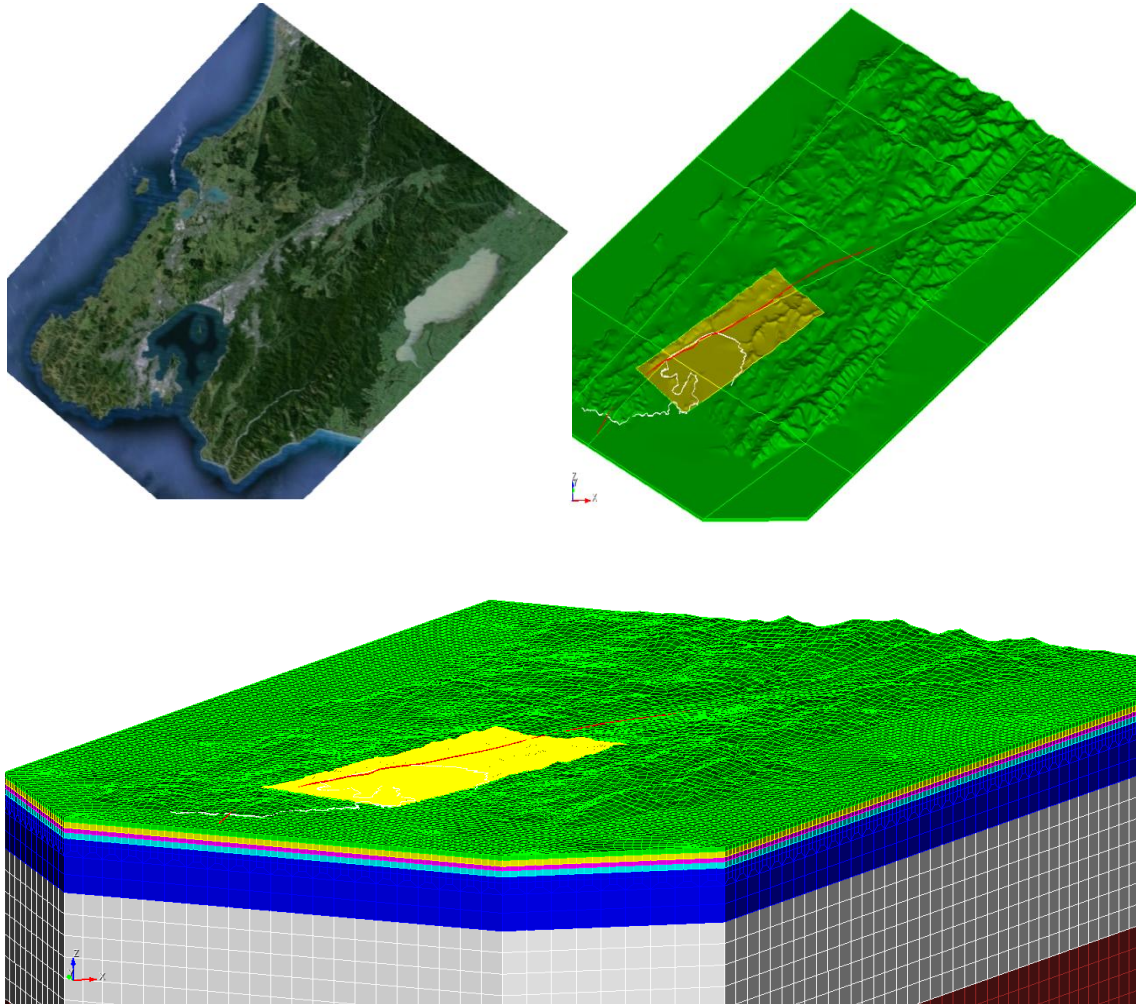


Wellington, New Zealand (from Google Earth)





Spectral Element Model



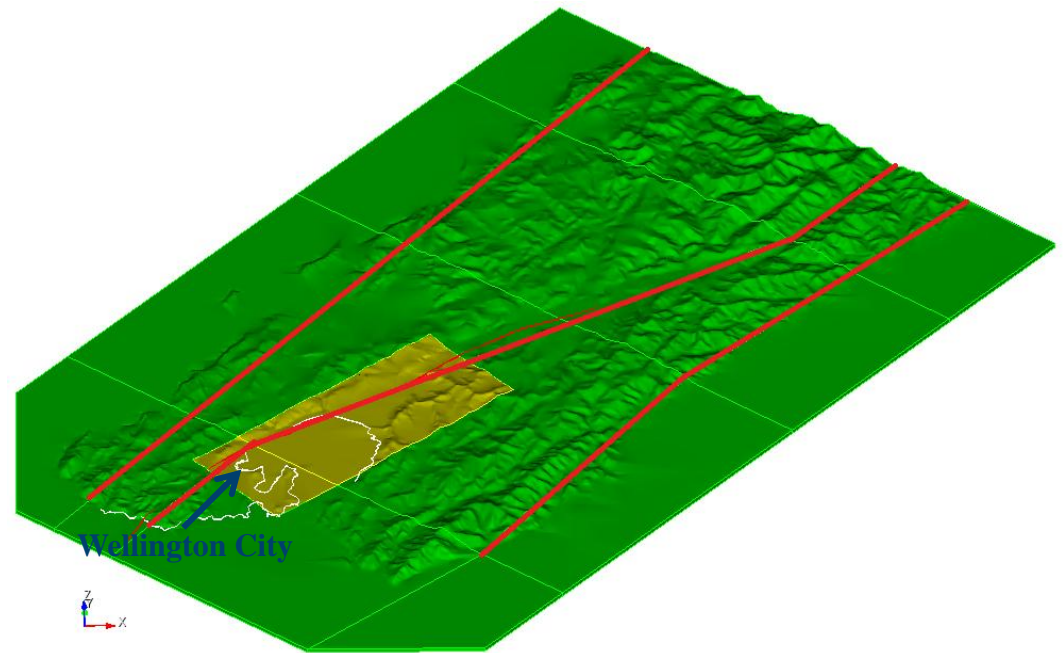
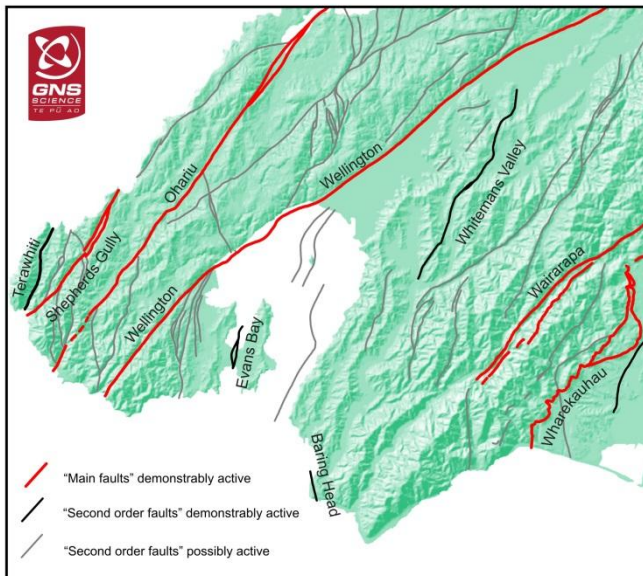
Wellington, New Zealand.
Topography exported in Cubit.
In yellow is represented the
Wellington - Lower Hutt basin;
superimposed are the coast
line and the Wellington fault
line.

The 3D hexahedral mesh of
the area, the mesh covers an
area of approximately 50 x 80
x 45 km and is composed by
around 350,000 hexahedra.
Around 200,000 elements are
in the Wellington-Lower Hutt
basin.



Kinematic Source Model:

Main Active Faults in Wellington

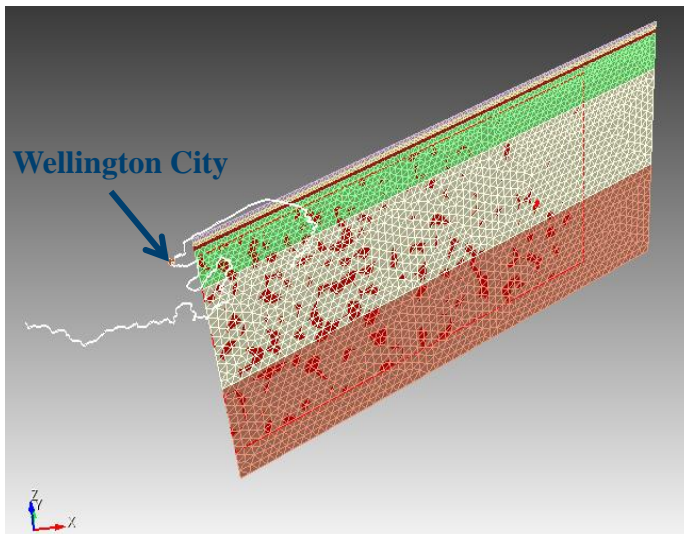


Main active faults in Wellington (source: GNS web site) and their representation in the numerical model. The model includes, from West to East, the Ohariu, the Wellington and the Wairarapa faults (superimposed red lines).

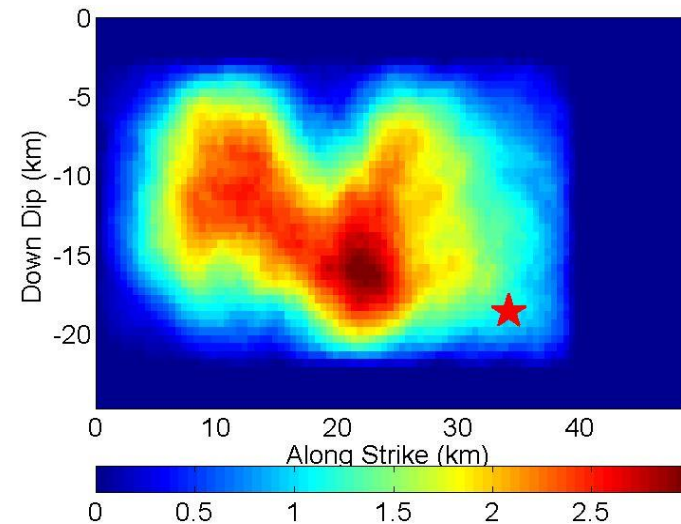


Scenario Properties:

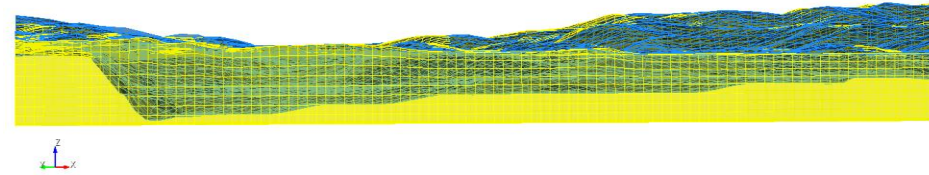
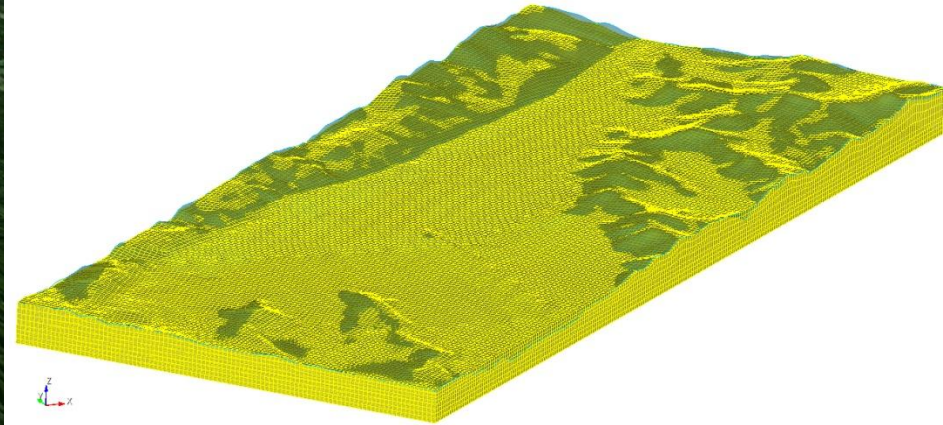
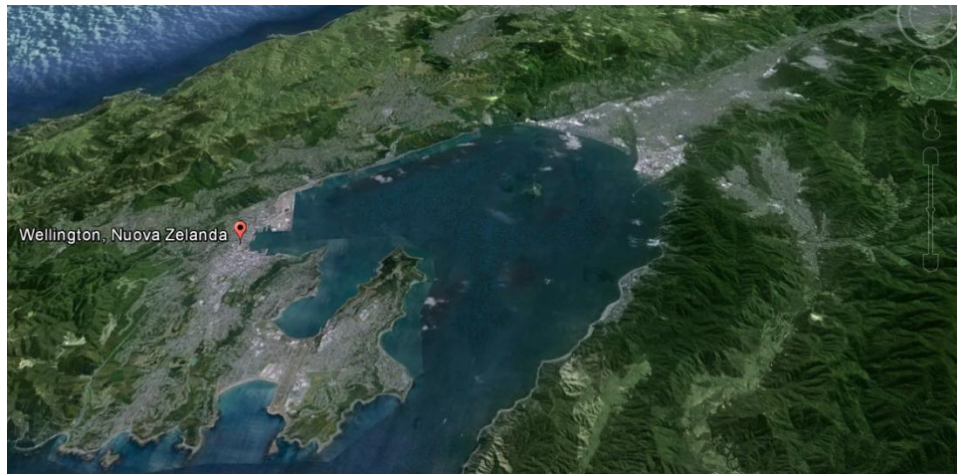
Selected scenario with **MAGNITUDE** of 7.0, length and width of 40000 and 20000 m, rupture velocity of 2700 m/s, rise time of 0.5 second and rake angle of 180 degree.



Fault model with strike angle of 58.2623° and dip of 90°



K-square self-similar slip distribution model proposed by Herrero and Bernard (1994)



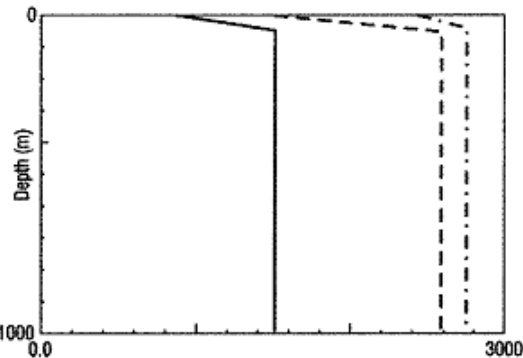
From top to bottom: Basin model in Cubit having size 10x22x0.7 km and element size of 100 m. The bedrock surface is exploited according a Not-honoring technique.

From top to bottom: representation on Google Earth and bedrock model from data provided by R. Benites.



Properties of the Wellington Basin (adapted from Benites et al. 2005)

Site 1



Bay

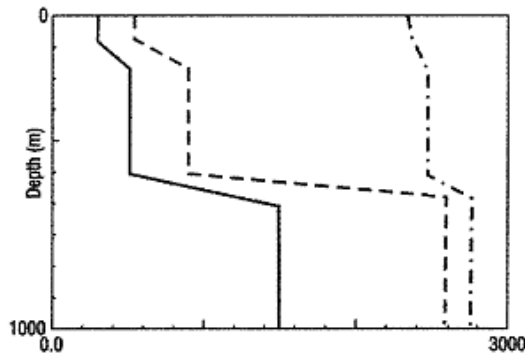
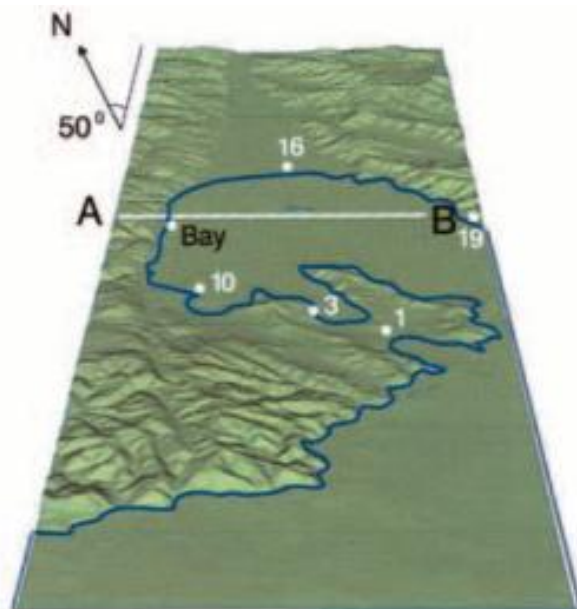
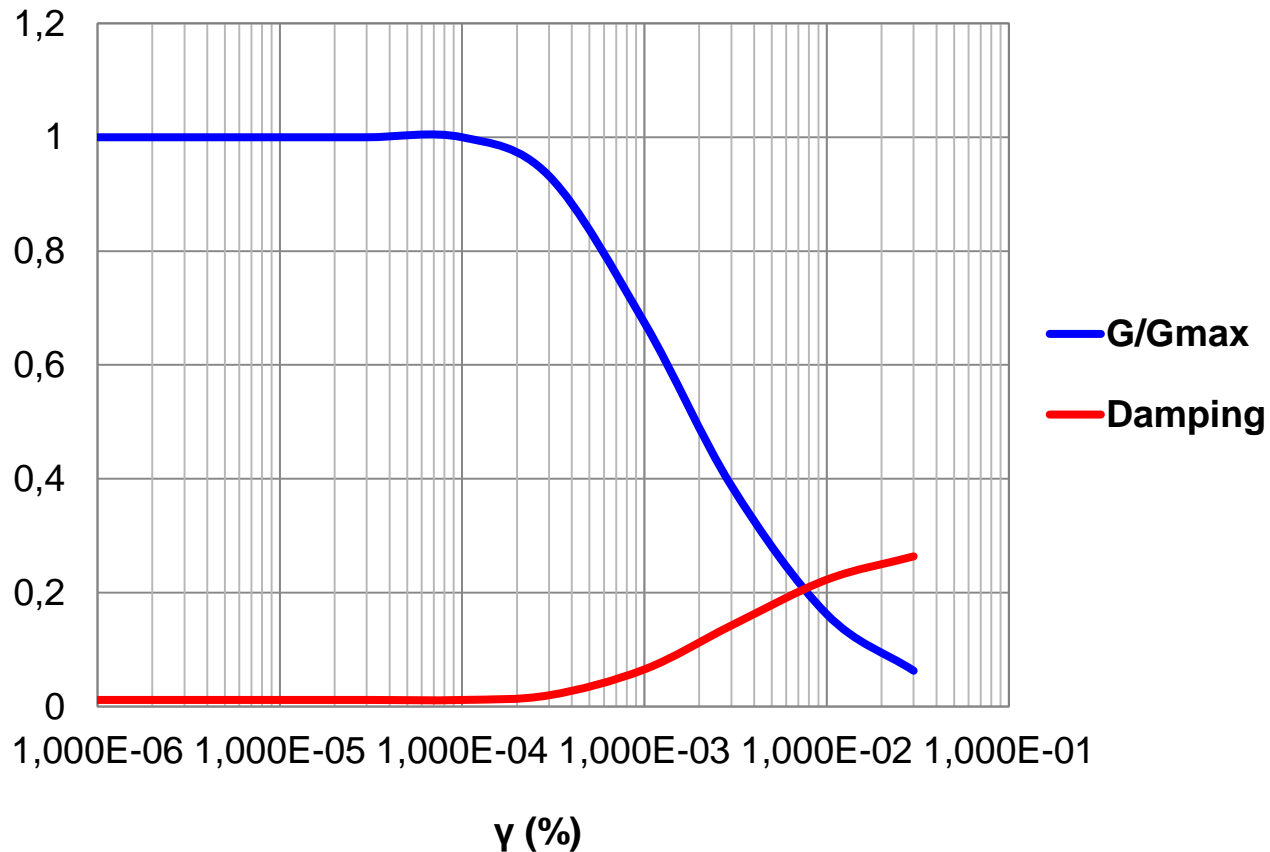


Table 1
3D Crustal Model Specification

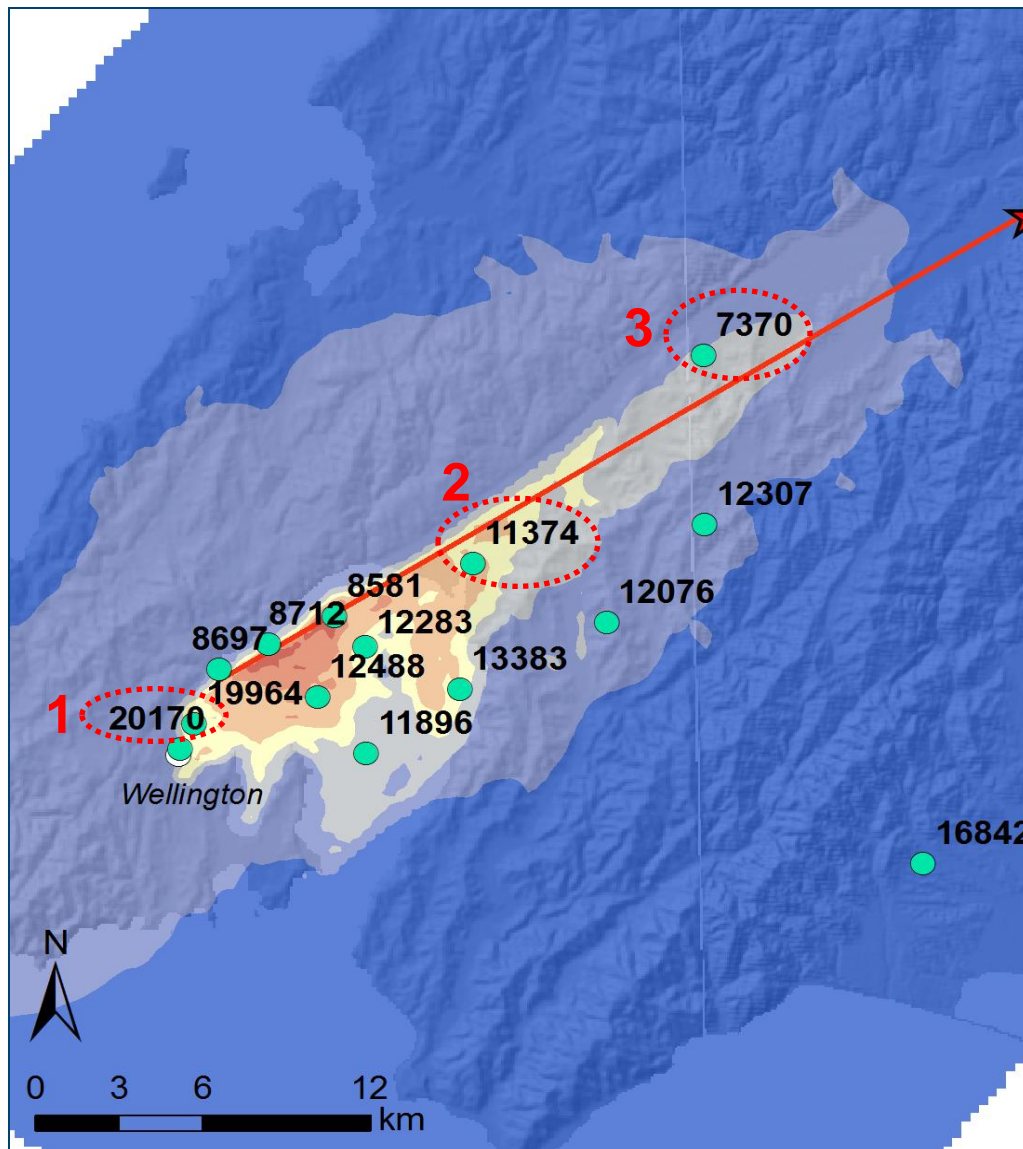
Description	S-Wave Velocity (m/sec)	Density (kg/m ³)
Soft Last Glacial sediments	300	2200
Stiff Last Interglacial sediments	330	2275
Poorly consolidated Waimea sediments	460	2359
Poorly consolidated Kororo Interglacial sediments	475	2365
Stiff Waimaunga Glacial sediments	610	2415
Stiff Brunswick Interglacial sediments	615	2417
Stiff weathered undifferentiated sediments	700	2421
Lithified, fractured basement rock (graywacke)	1500	2744

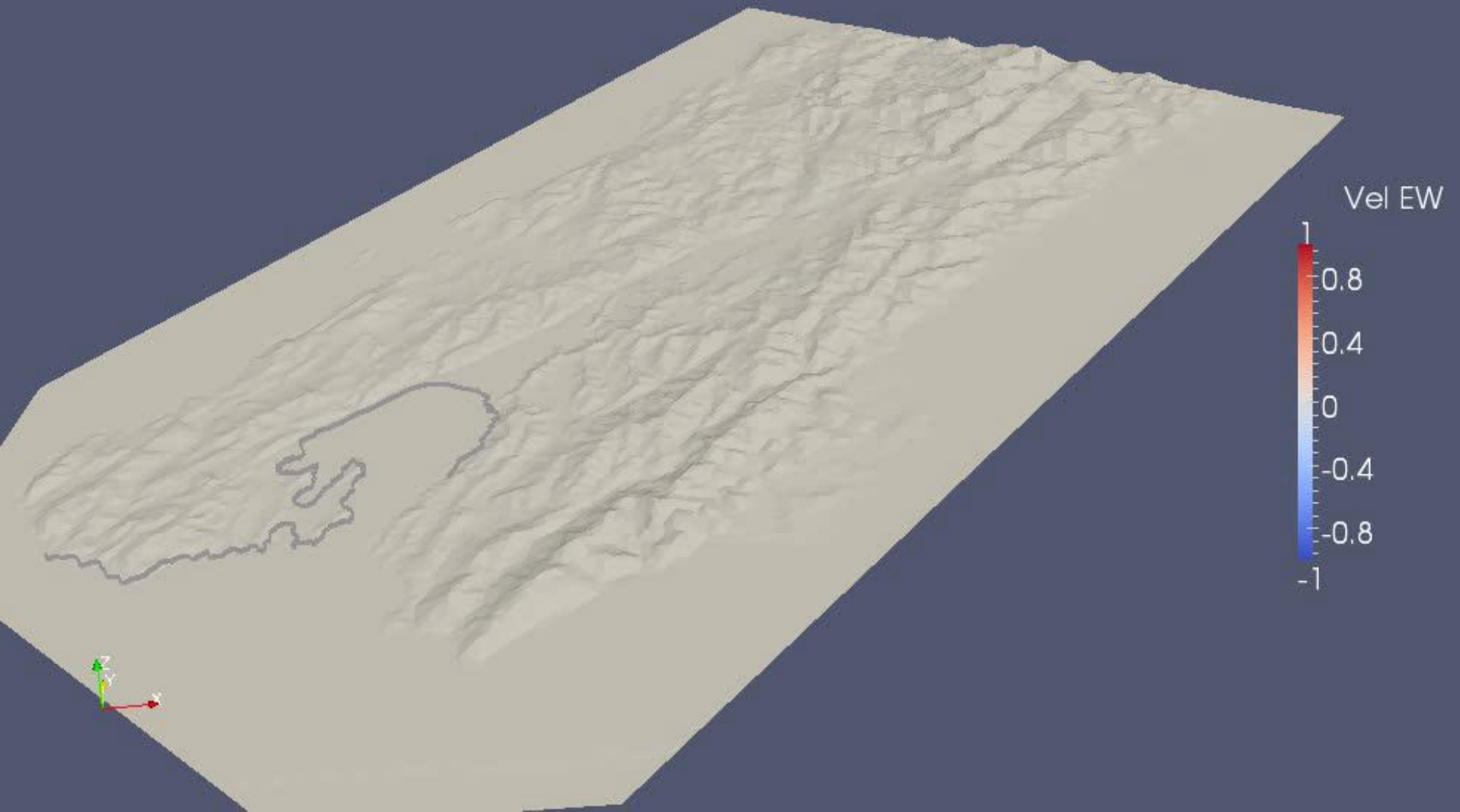


	z (m)	Vs (m/s)	Vp (m/s)	ρ (kg/m ³)
Alluvial Basin	≤ 100	300	520	2200
	100 < ≤ 200	400	700	2300
	200 < ≤ 500	500	850	2400
	> 500	1000	1700	2400
Outcropping Bedrock	200 < ≤ 500	1500	2800	2400



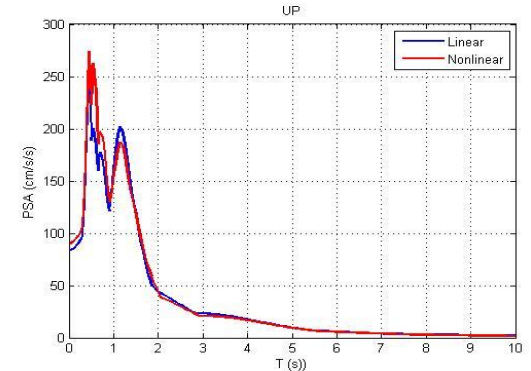
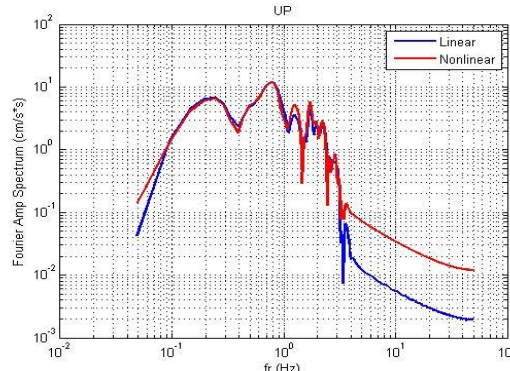
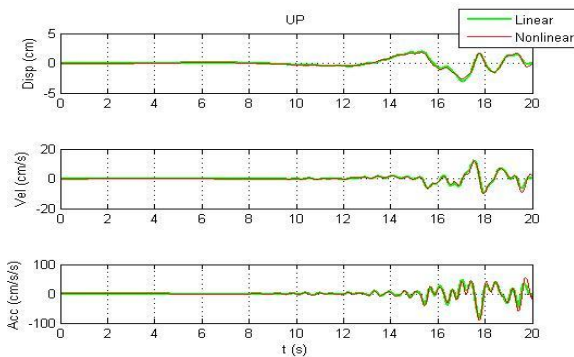
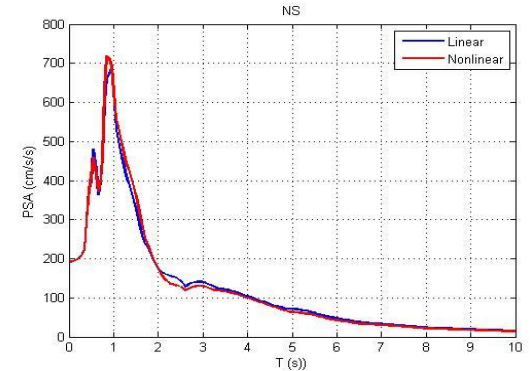
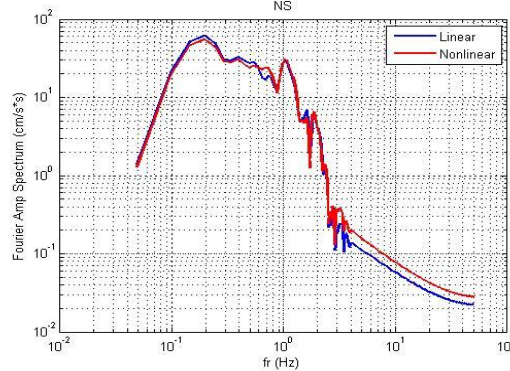
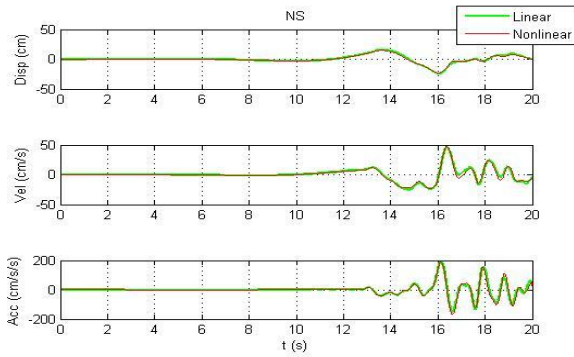
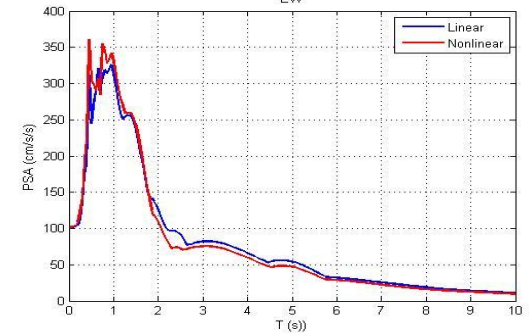
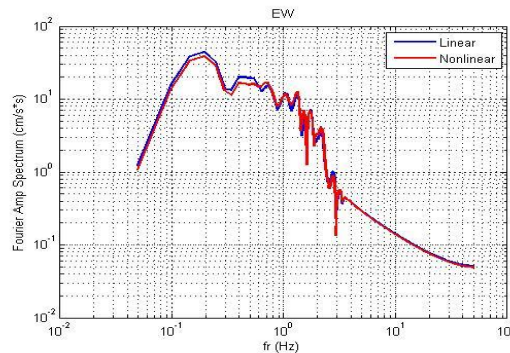
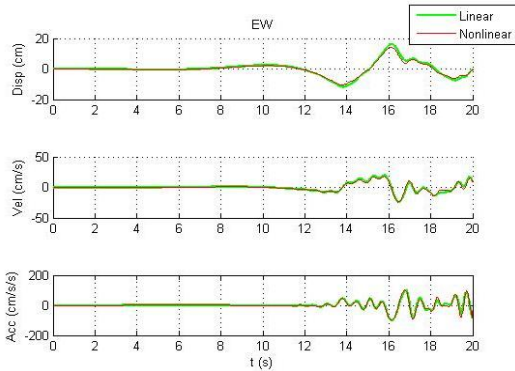
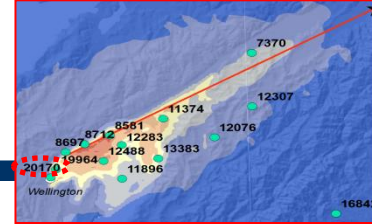
G/G0 and damping curves applied to the alluvial basin (first 200m of soil layer)





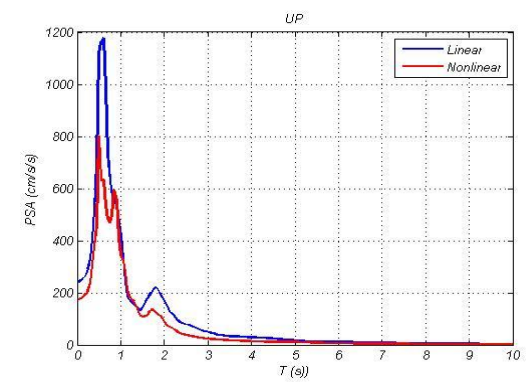
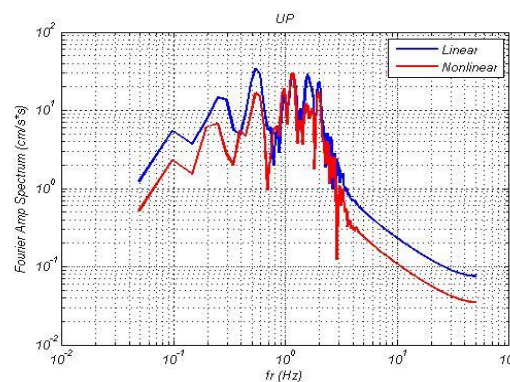
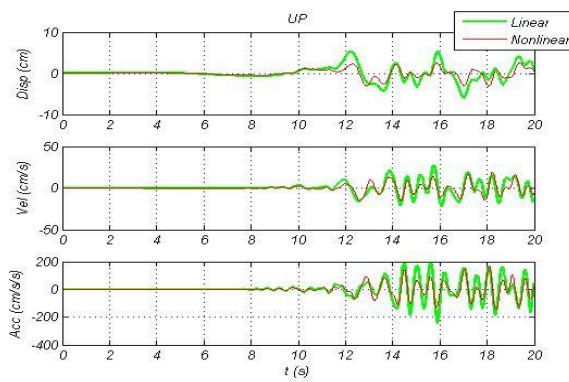
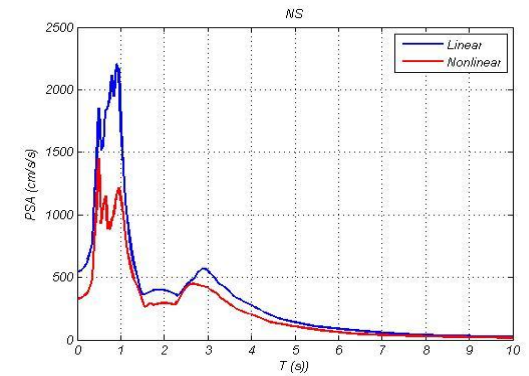
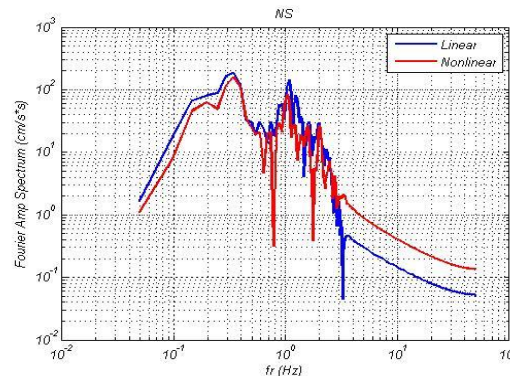
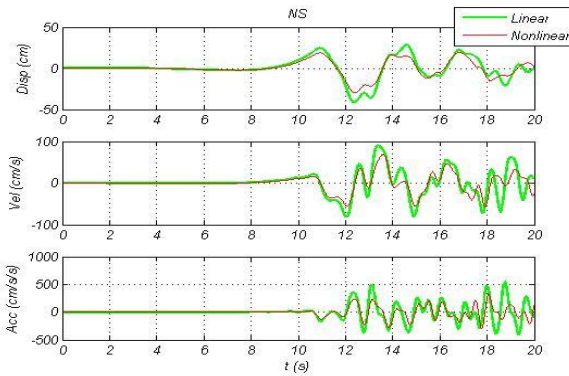
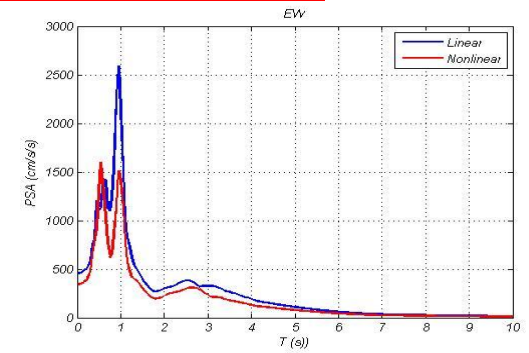
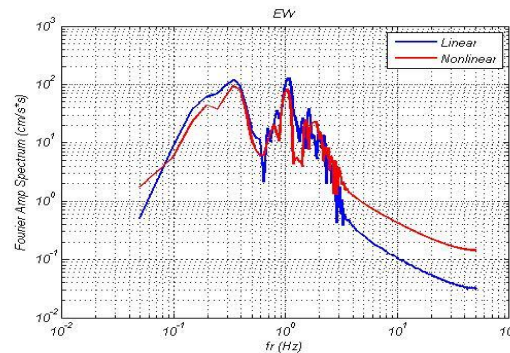
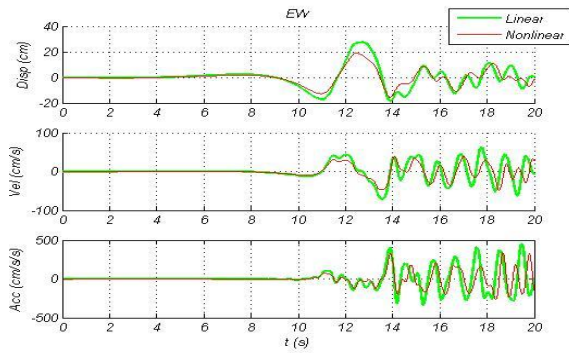
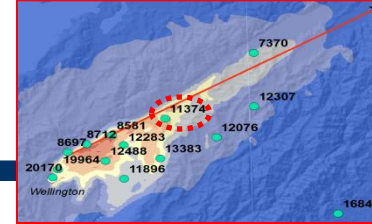


Preliminary Results – Monitor #20170



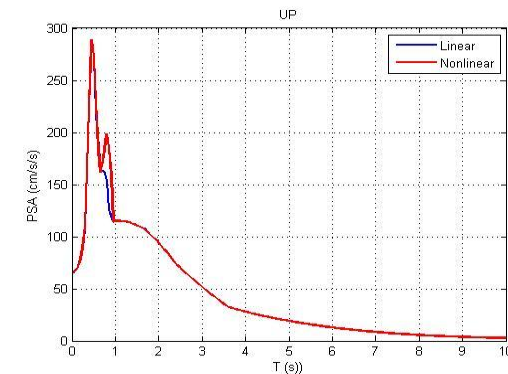
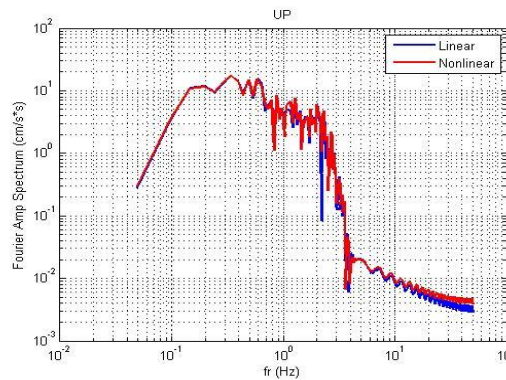
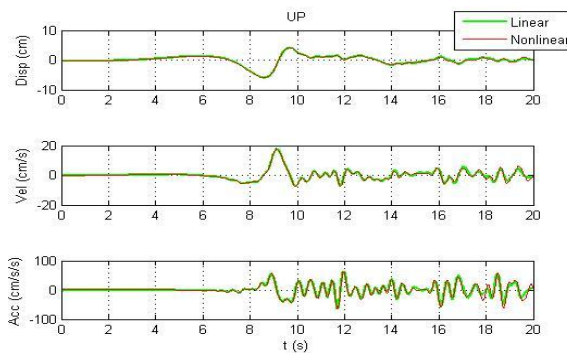
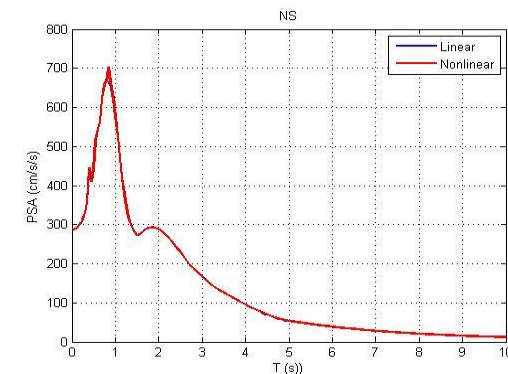
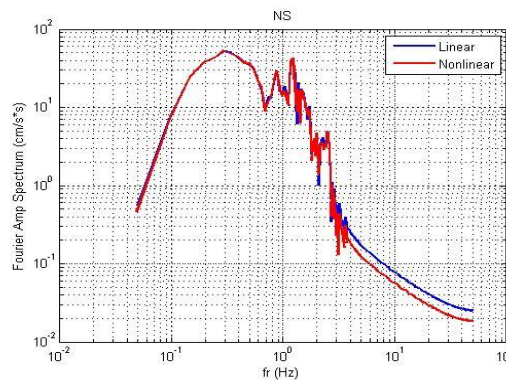
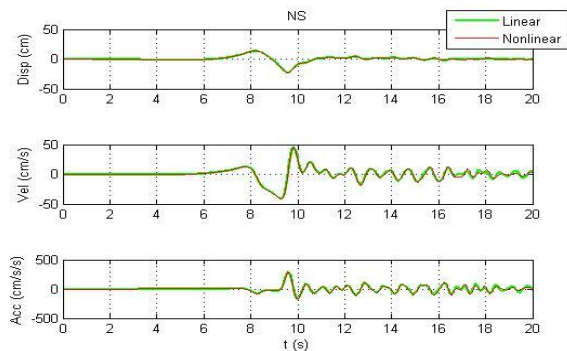
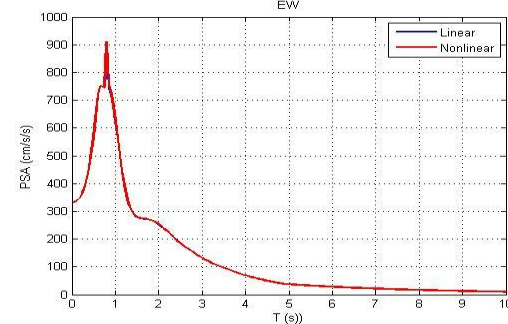
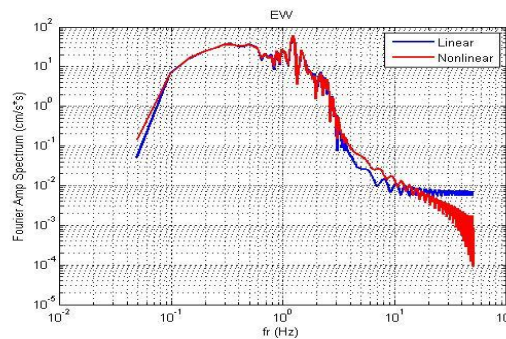
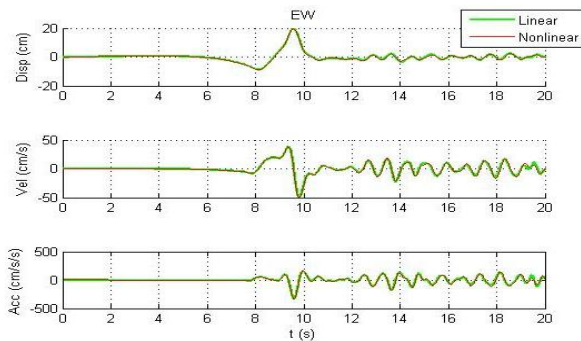
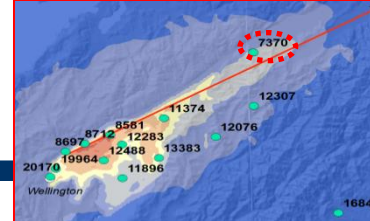


Preliminary Results – Monitor #11374



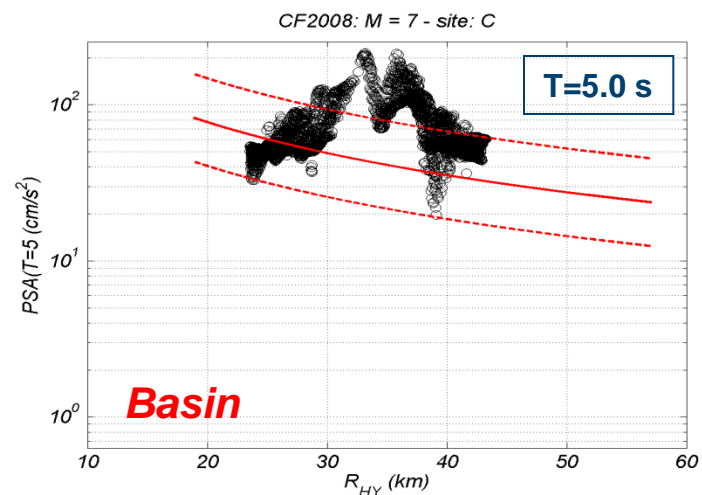
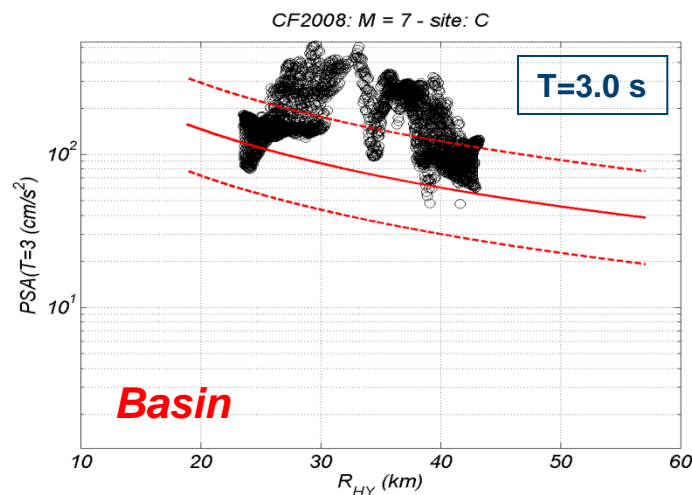
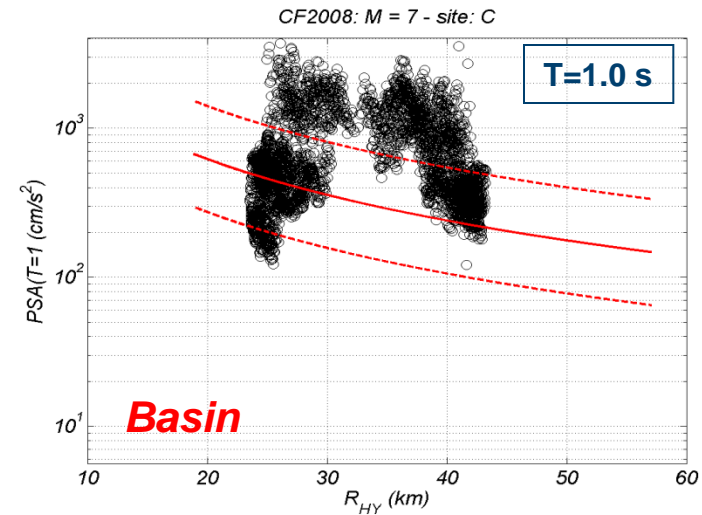
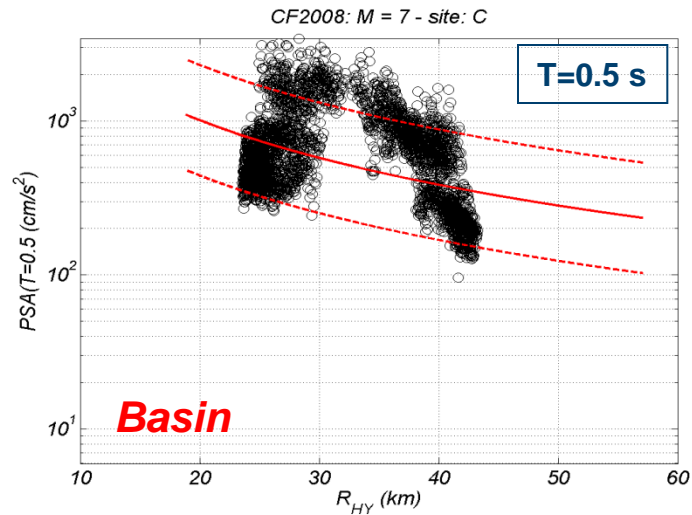


Preliminary Results – Monitor #7370



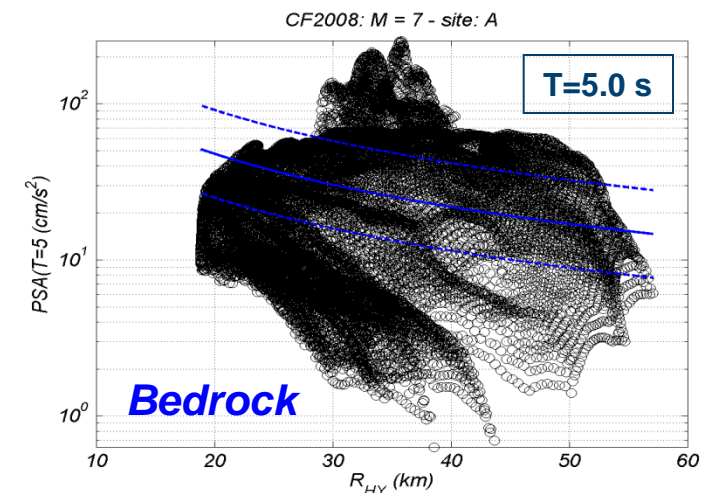
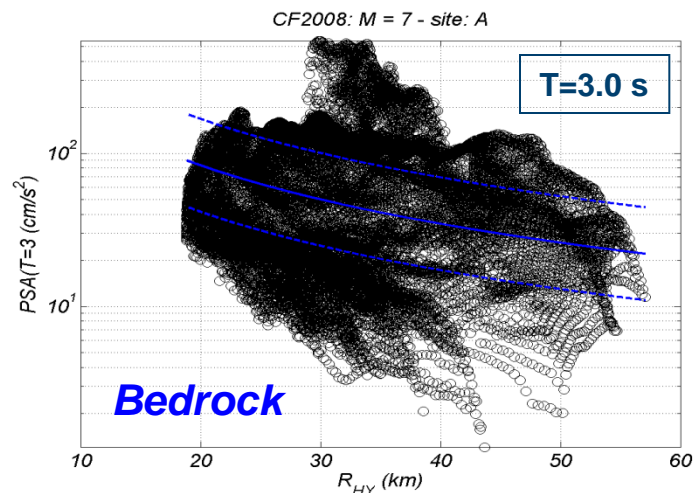
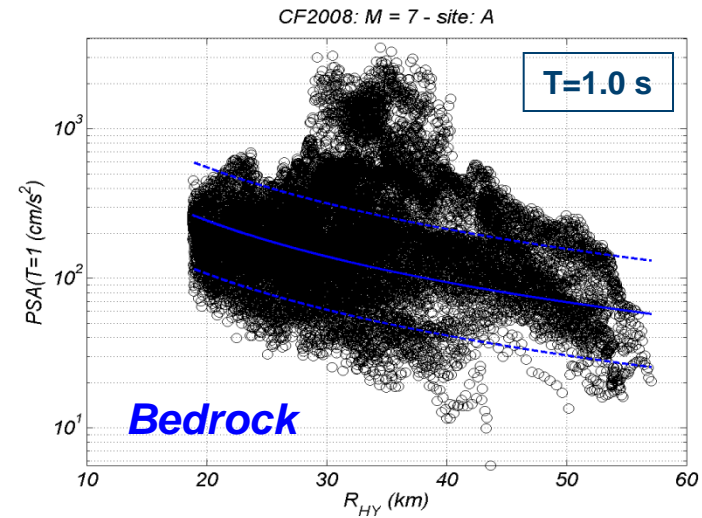
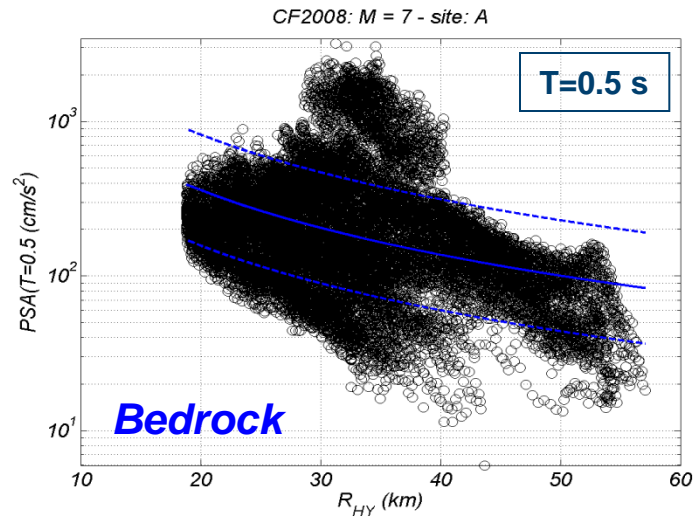
Comparison with GMPEs - Nonlinear Analysis

PSA at selected periods: comparison with Cauzzi & Faccioli (2008)



Comparison with GMPEs - Nonlinear Analysis

PSA at selected periods: comparison with Cauzzi & Faccioli (2008)

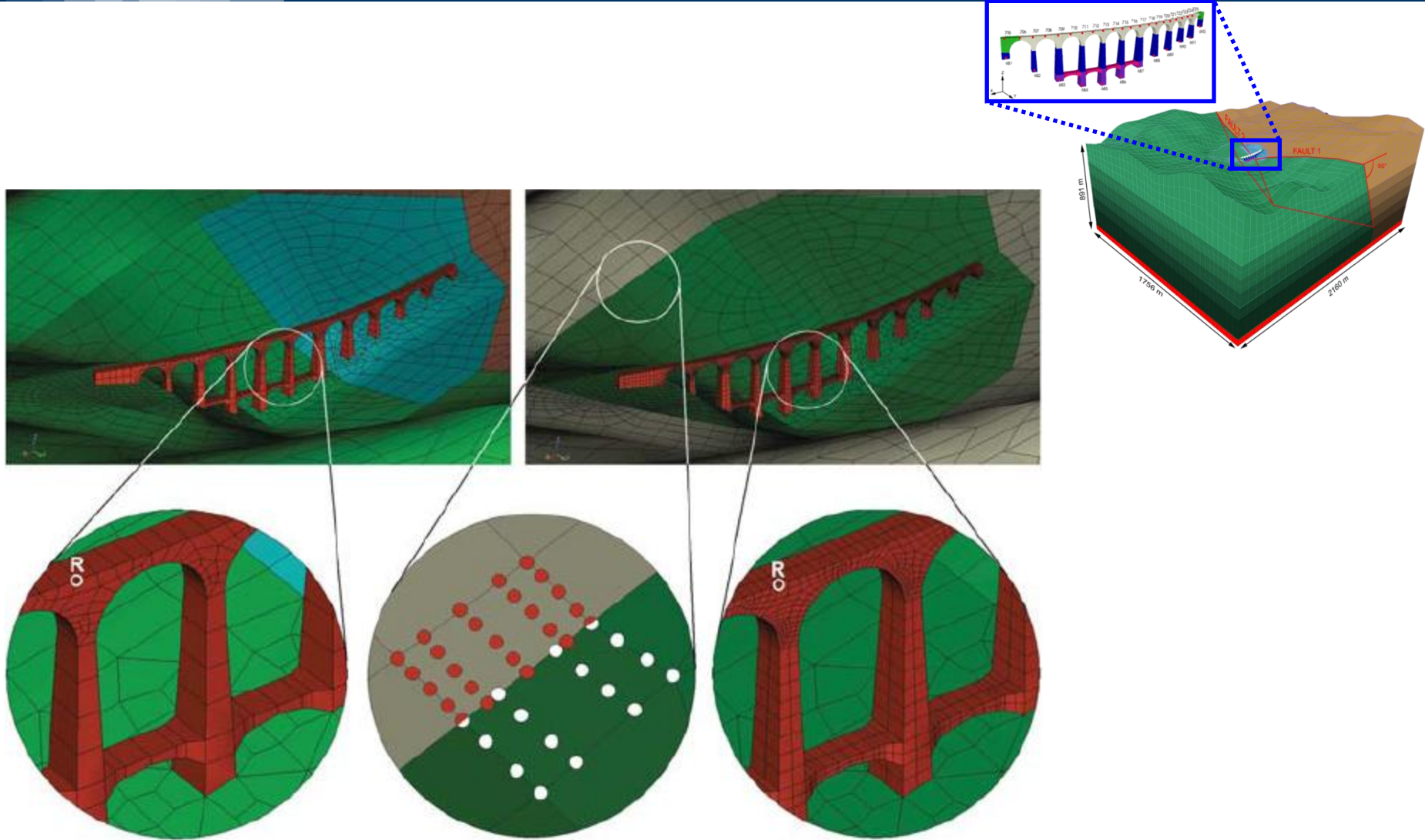




- ✓ 1a) costruzione di una prima versione del sito web che conterrà: (a) i codici utilizzati e i link per scaricarli (SPEED, Hisada, ... ? ...); (b) sintesi dei benchmark e casi studio trattati nel progetto (L'Aquila, Emilia); → da fare confluire successivamente in Synthesis
- ✓ 1b) routine comuni di pre-processing (costruzione dell'input in termini di spostamento sulla faglia per eccitazione broad-band) e post-processing (generazione di accelerogrammi broad-band con approccio ibrido deterministico+stocastico)
- ✓ 1c) nuova versione codice SPEED (con updates da parte di varie UR)
- ✓ 1d) benchmark di confronto tra i codici
- ✓ 1e) completamento simulazioni terremoto L'Aquila
- ✓ 1f) completamento simulazioni terremoto Emilia



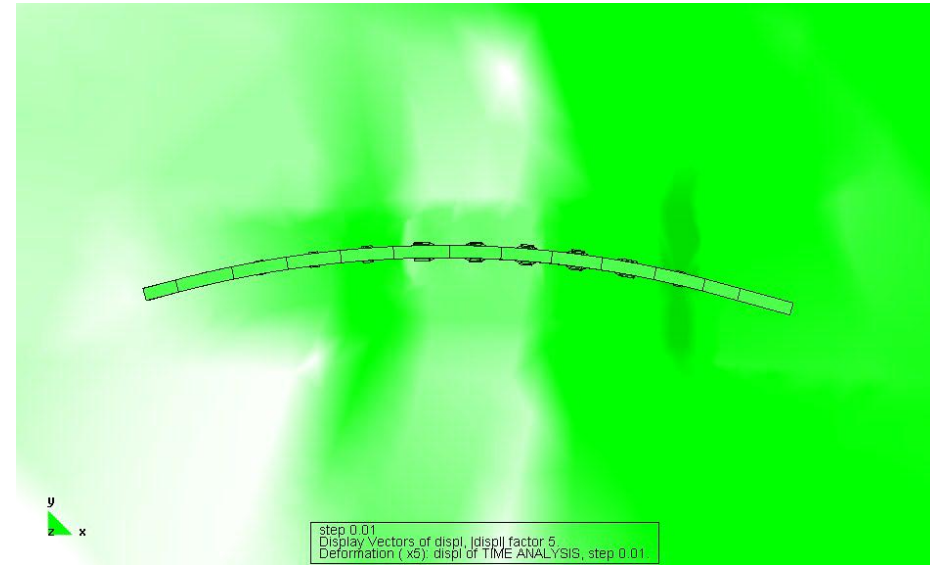
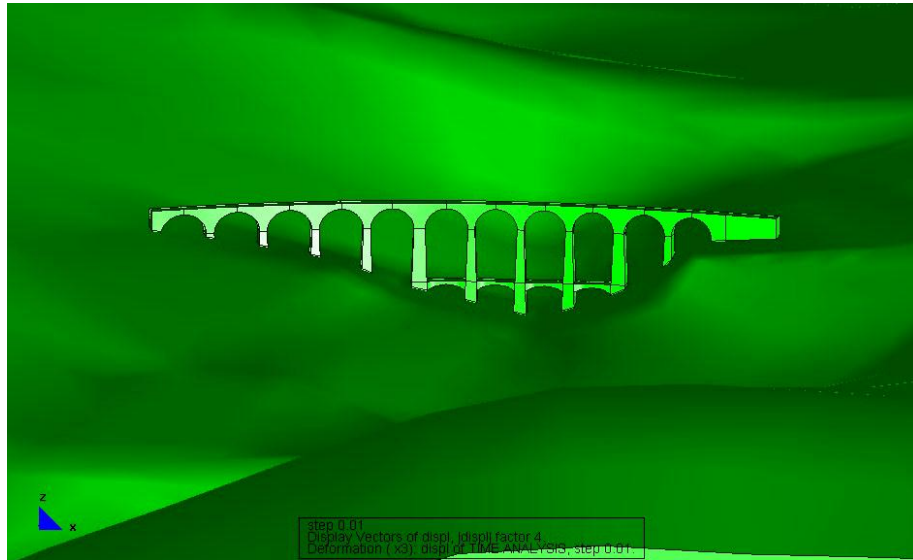
Obiettivo 4-5: coerenza del moto in n.s. e risposta strutture estese



mesh conforme

mesh non conforme

Obiettivo 4-5: coerenza del moto in n.s. e risposta strutture estese

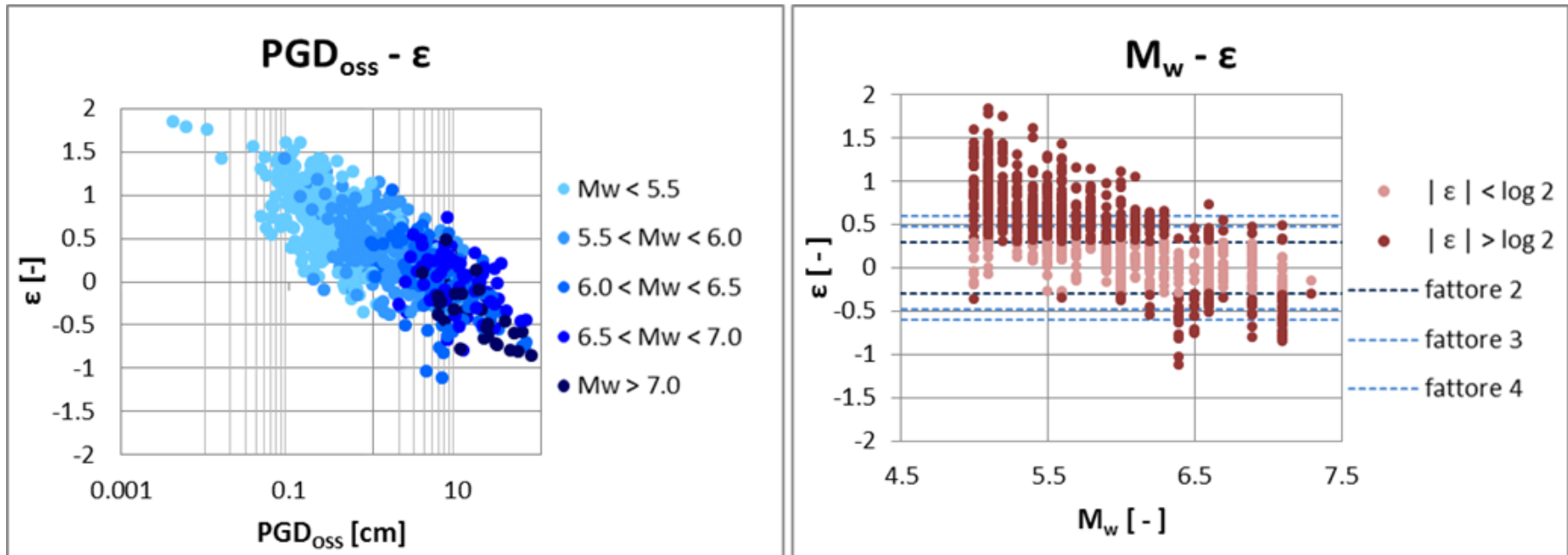




Le formule adottate nelle norme sono idonee ?

$$d_g = 0.025 \cdot a_g \cdot S \cdot T_C \cdot T_D$$

$$\varepsilon = \log \left(\frac{PGD_{norm}}{PGD_{oss}} \right) \leftarrow \text{valori di PGD osservati dal database SIMBAD}$$





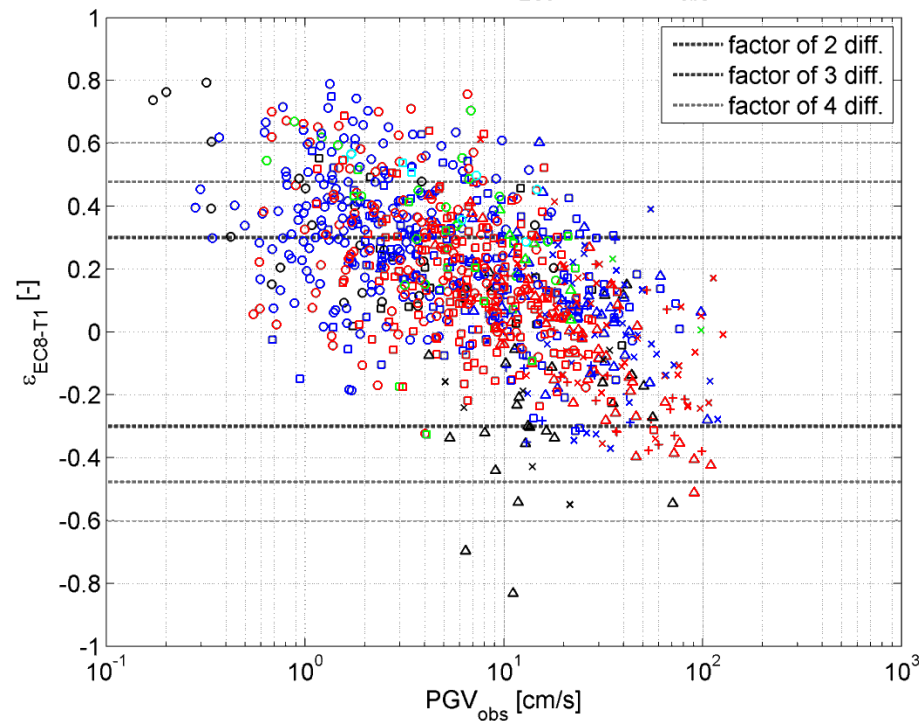
Le formule adottate nelle norme sono idonee ?

$$v_g = 0.16 \cdot a_g \cdot S \cdot T_C$$

$$\varepsilon = \log \left(\frac{PGV_{norm}}{PGV_{oss}} \right)$$

← valori di PGV osservati dal database SIMBAD

All data: $\varepsilon = \log(PGV_{EC8}) - \log(PGV_{obs})$





Le formule adottate nelle norme sono idonee ?

3.2.5.2 Spostamento assoluto e relativo del terreno

Il valore dello spostamento assoluto orizzontale massimo del suolo (d_g) può ottenersi utilizzando l'espressione 3.2.15.

Nel caso in cui sia necessario valutare gli effetti della variabilità spaziale del moto richiamati nel paragrafo precedente, il valore dello spostamento relativo tra due punti i e j caratterizzati dalle proprietà stratigrafiche del rispettivo sottosuolo ed il cui moto possa considerarsi indipendente, può essere stimato secondo l'espressione seguente:

$$d_{ij\max} = 1,25\sqrt{d_{gi}^2 + d_{gj}^2} \quad (3.2.18)$$

dove d_{gi} e d_{gj} sono gli spostamenti massimi del suolo nei punti i e j , calcolati con riferimento alle caratteristiche locali del sottosuolo.

Il moto di due punti del terreno può considerarsi indipendente per punti posti a distanze notevoli, in relazione al tipo di sottosuolo; il moto è reso indipendente anche dalla presenza di forti variabilità orografiche tra i punti.



Le formule adottate nelle norme sono idonee ?

In assenza di forti discontinuità orografiche, lo spostamento relativo tra punti a distanza x si può valutare con l'espressione:

$$d_{ij}(x) = d_{ij0} + (d_{ij\max} - d_{ij0}) \left[1 - e^{-1,25(x/v_s)^{0,7}} \right], \quad (3.2.19)$$

dove v_s è la velocità di propagazione delle onde di taglio in m/s e d_{ij0} , spostamento relativo tra due punti a piccola distanza, è dato dall'espressione

$$d_{ij0}(x) = 1,25 |d_{gi} - d_{gj}|. \quad (3.2.20)$$

Per punti a distanza inferiore a 20 m lo spostamento relativo, se i punti ricadono su sottosuoli differenti, è rappresentato da d_{ij0} ; se i punti ricadono su sottosuolo dello stesso tipo, lo spostamento relativo può essere stimato, anziché con l'espressione 3.2.19, con le espressioni

$$d_{ij}(x) = \frac{d_{ij\max}}{v_s} \cdot 2,3x \quad \text{per sottosuolo tipo D}, \quad (3.2.21)$$

$$d_{ij}(x) = \frac{d_{ij\max}}{v_s} \cdot 3,0x \quad \text{per sottosuolo di tipo diverso da D}.$$



Le formule adottate nelle norme sono idonee ?

In assenza di forti discontinuità orografiche, lo spostamento relativo tra punti a distanza x si può valutare con l'espressione:

$$d_{ij}(x) = d_{ij0} + (d_{ij\max} - d_{ij0}) \left[1 - e^{-1,25(x/v_s)^{0,7}} \right], \quad (3.2.19)$$

dove v_s è la velocità di propagazione delle onde di taglio in m/s e d_{ij0} , spostamento relativo tra due punti a piccola distanza, è dato dall'espressione

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$$d_{ij}(x) = \frac{d_{ij\max}}{v_s} \cdot 3,0x \quad \text{per sottosuolo di tipo diverso da D}.$$

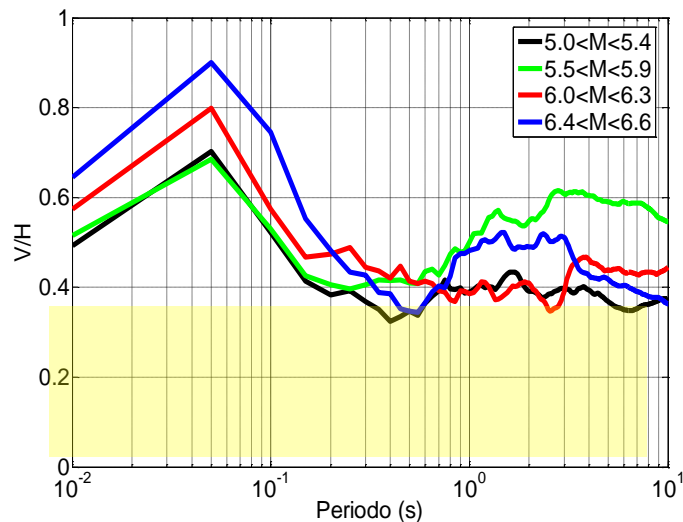


Obiettivo 6: indicazioni normative

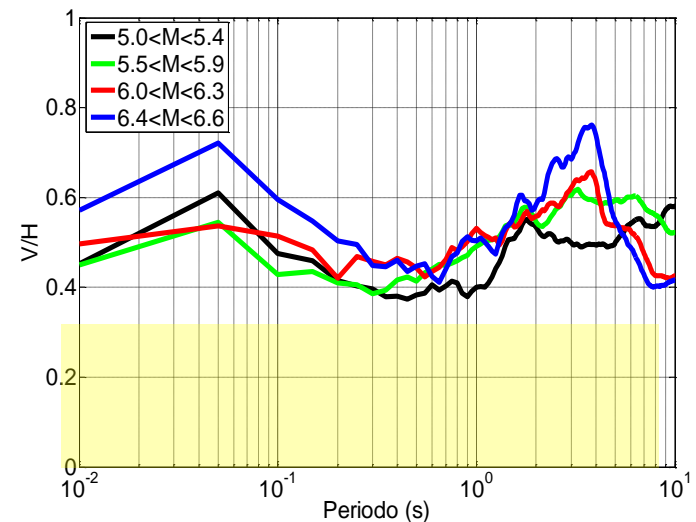
Le formule adottate nelle norme sono idonee ?

Rapporti spettrali V/H: effetto della magnitudo

$10 < d_f < 30$ km



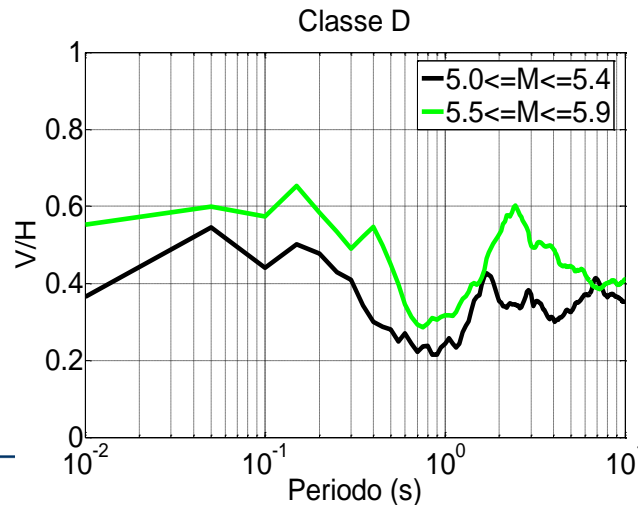
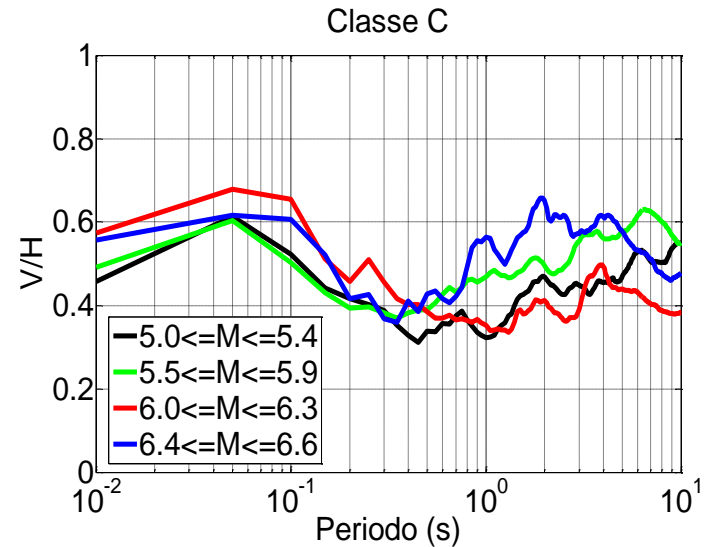
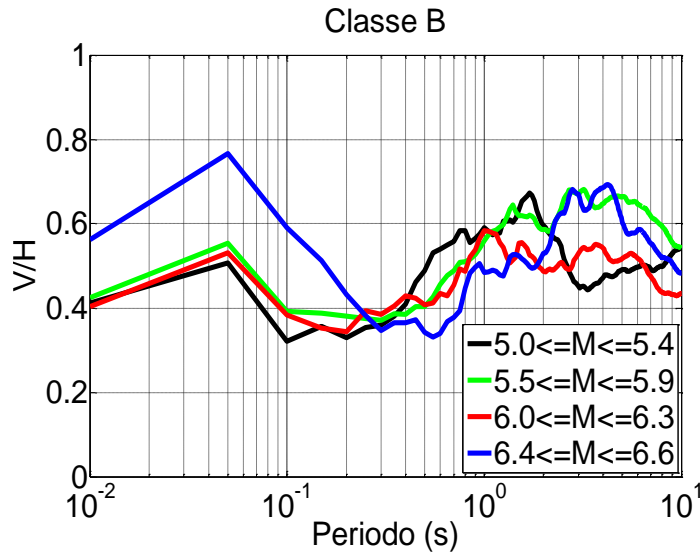
$30 < d_f < 50$





Obiettivo 6: indicazioni normative

Rapporti spettrali V/H: effetto del sito





Obiettivo 6: indicazioni normative

Rapporti spettrali V/H: confronto con EC8

