Ground response analysis for seismic microzonation studies

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Introduction

The areas with high **hydro-geological risk** (i.e. landslide and/or flood risk) represent about **10% of the Italian territory** (29500 sq. km) and affect **89% of the municipalities** (6631)

The population living in areas with high hydro-geological risk is equal to 5.8 million people (**9.6% of the population**), for a total of 2.4 million families and over 1.2 million buildings

→ ***A tenth of the population lives in hydro-geological risk areas***

The areas with high **seismic risk** are around **44% of the national territory** (131000 sq. km), affecting **36% of the municipalities** (2893)

21.8 million people live in areas with high seismic risk (**36% of the population**), for a total of 8.6 million families and approximately 5.5 million residential and non-residential buildings

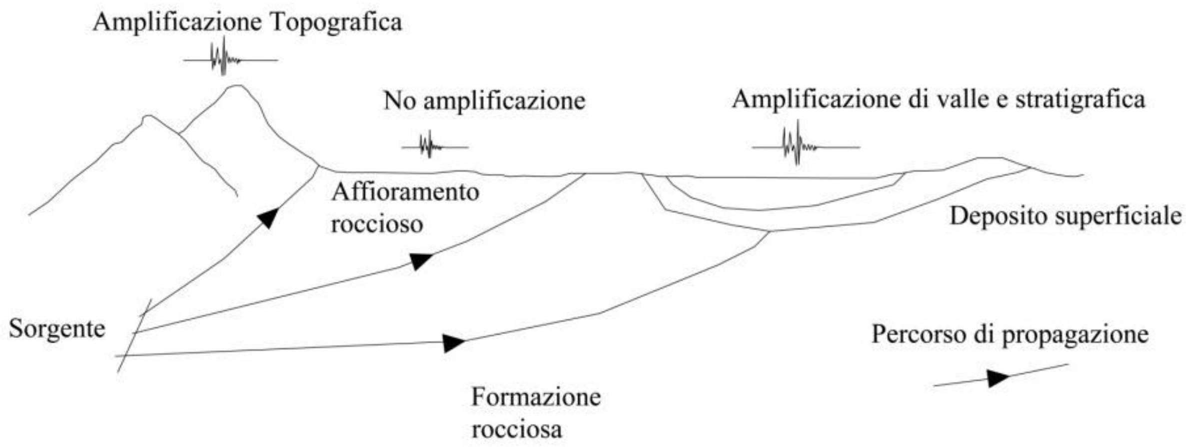
→ ***One in three Italians lives in seismic risk areas***

Source: ANCE (National Association of Builders) snapshot @ 2012

Introduction

After an earthquake, the observation of the damage caused to buildings and infrastructures often highlights substantial differences in urban centers even at a small distance between them. In some cases, collapses and considerable damage are observed in locations that are located at great distances from the epicenter

The quality of the buildings (i.e. their vulnerability) can affect the extent of the damage, but often the causes must be sought in a different **local seismic hazard**, also determined by the different way in which the earthquake propagates in relation to the **thickness** and **geo-mechanical characteristics** of the soils of the superficial layers, or by the instability of the soil



Introduction

The **aim** of the Seismic Microzonation (MS) studies is to assess the local seismic hazard by **identifying areas** of the territory characterised by a **homogeneous seismic behaviour**

The **objectives** are:

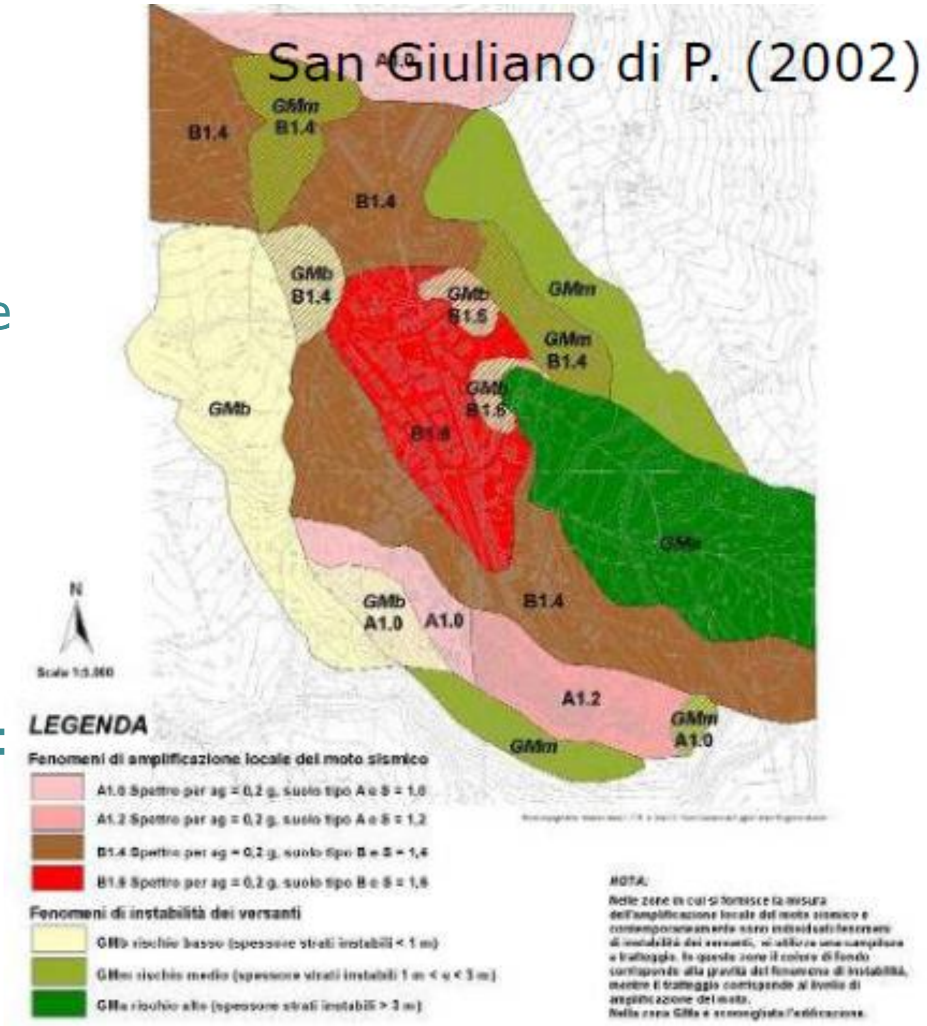
- to rationalise the knowledge of the alterations of the seismic action at ground surface

- to highlight the occurrence of possible amplification phenomena linked to the stratigraphic and morphological characteristics of the area and instability phenomena due to permanent deformations induced by the earthquake (e.g. landslides, liquefaction)

- to provide useful information for the governance of the territory, for the design, urban and emergency planning and post-earthquake reconstruction

Seismic microzonation in Italy before 2008

- MS after the seismic event
- No standard for site investigations
- No cartographic and archiving standards
- Few applications in the governance of the territory



After the Molise earthquake of 2002:

first attempt to develop standards and guidelines for the evaluation of local site effects

Source: Protezione Civile (DPC)

The Guidelines and Criteria of 2008 (ICMS08)

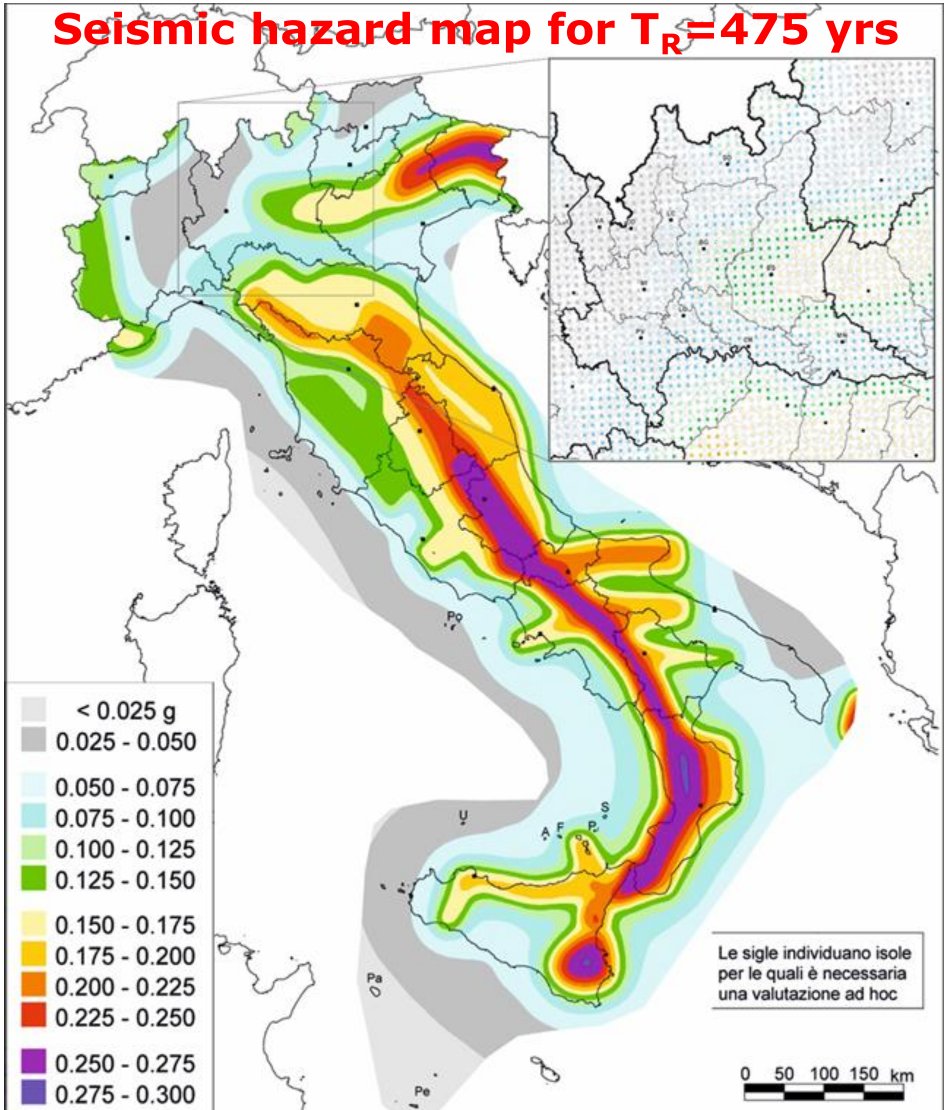
On the 11th of November 2008, the Conference of Regions and Autonomous Provinces approves the "Guidelines and Criteria for seismic microzonation"

First extensive application of the ICMS08 after the L'Aquila earthquake of 2009 → release of the Law n. 39 (28.4.2009)

Article 11 of the Law n. 39 contemplates that the interventions for the seismic risk prevention are funded nationwide and allocates 965 million euros in 7 years

Source: Protezione Civile

Introduction



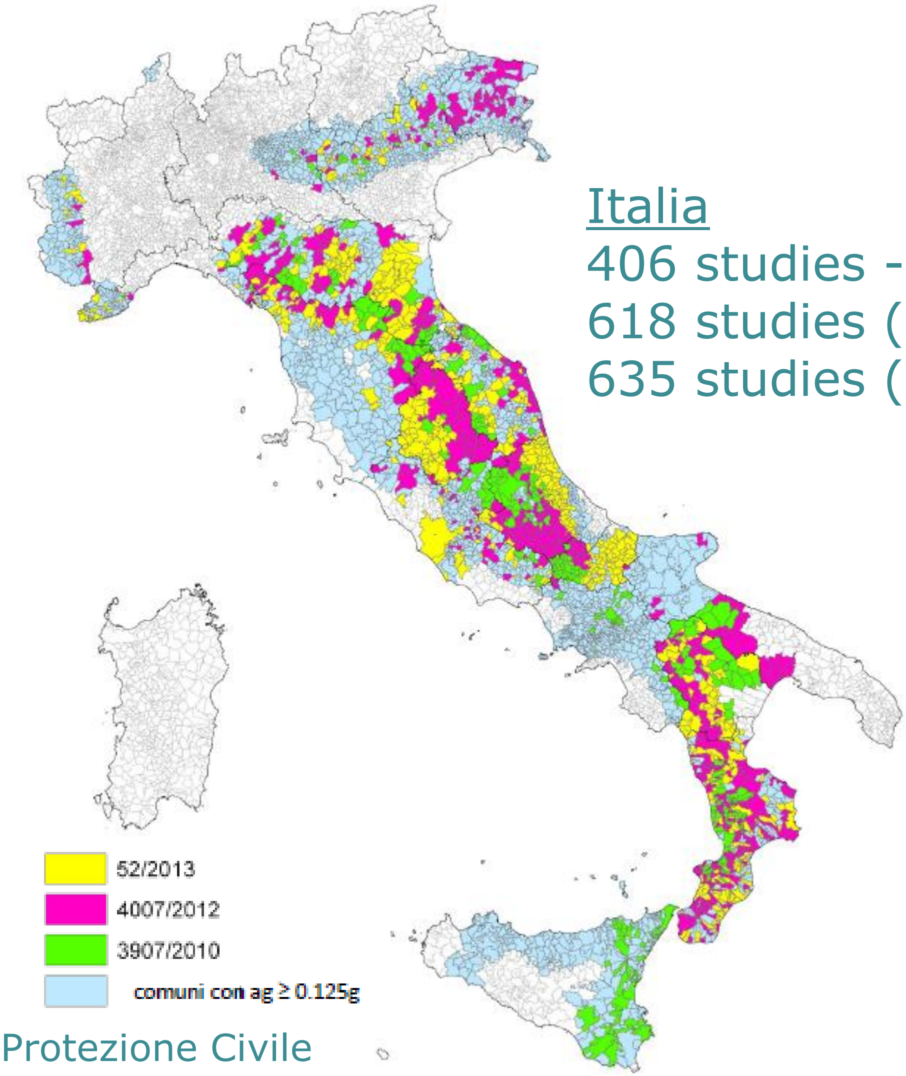
Source: Protezione Civile

The implementation of art. 11 is delegated to the Department of Civil Protection (DPC) and regulated through ordinances of the Presidente del Consiglio dei Ministri

Funding is intended for areas or buildings located where $a_g \geq 0.125g$

Competence Center (agreement between DPC and CNR-IGAG)
-Secretariat
-Technical structure for the management of the archiving system
-Technical structure for preliminary investigation and verification

MS studies - 2014

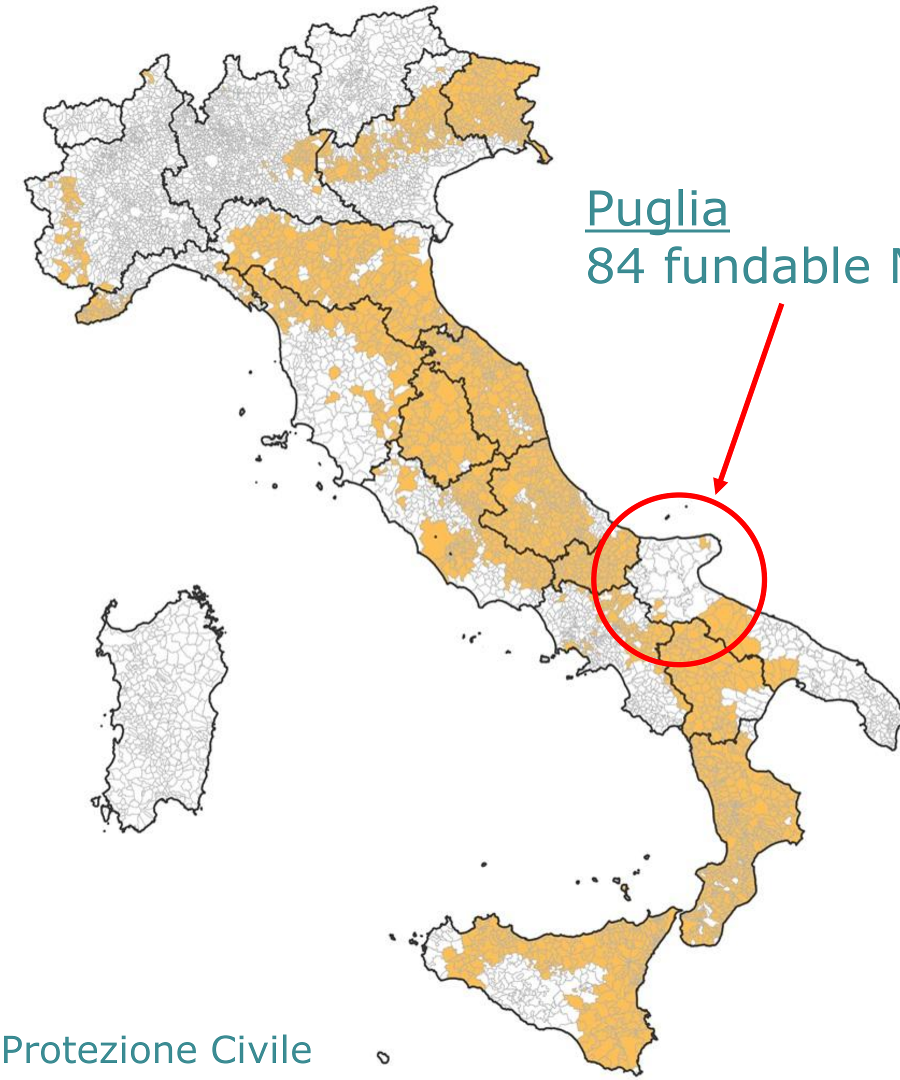


Italia
406 studies - OPCM 3907/2010
618 studies (444 CLE) - OPCM 4007/2012
635 studies (49 CLE) - OCDPC 52/2013
1659 in total

Source: Protezione Civile

snapshot @ 25.7.2014

MS studies - 2018



Puglia
84 fundable Municipalities

Source: Protezione Civile

snapshot @ 30.6.2018

Introduction

Results to date

- Intense and effective **collaboration** between the Italian State (DPC) and the Regions (ICMS08, L'Aquila earthquake)
- Establishment of a **common working method** and **language** among experts from different technical-scientific background (ICMS08, L'Aquila earthquake, Gruppo di lavoro_MS, Linee Guida)
- Definition of **cartographic** and **IT standards** (Tool for archiving geological, geotechnical and geophysical data: SoftMS)
- **Involvement** and **cultural enrichment** of geologists, engineers and architects (courses and seminars at national and regional level, framework agreements with professional associations)

Source: Protezione Civile

Introduction

Seismic Microzonation

Carta delle MOPS Level I

Evaluation of existing data, geological and geomorphological surveys

Synthesis of data and available maps

Carta di MS Level II

Geophysical investigations for the assessment of V_S

Charts for **amplification factors** and empirical formulas for slope instability and liquefaction

Carta di MS Level III

In-situ investigations for the evaluation of the V_S profile + laboratory geotechnical tests

Ground response analyses for **amplification effects** and dynamic simulations for permanent deformations

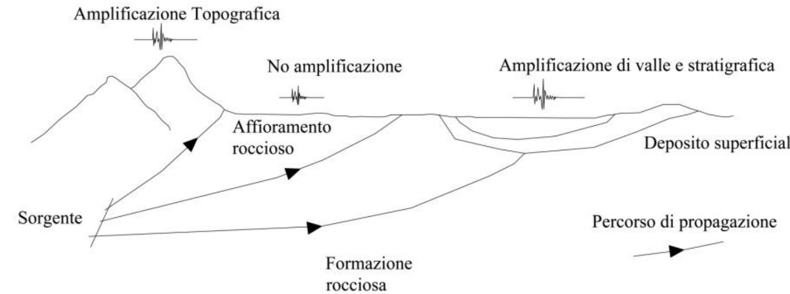
Ground Response Analysis

Introduction

Microzonation and **ground response analysis**

- MS studies are carried out in order to assess the local seismic hazard on a **territorial scale**, identifying areas of the territory characterised by a homogeneous seismic behaviour
- The analysis of local seismic response has the aim of evaluating, **in a specific site**, the set of alterations of the seismic motion in relation to the mechanical and geometric properties of the deposits close to the surface and/or the site topography
- The ultimate aim of MS studies is to draw **Seismic Microzonation Maps** using **Amplification Factors** (FA), i.e. synthetic indicators representative of the seismic amplification
- The product of a ground response analysis consists in defining the seismic motion at the surface of the construction site, in terms of **time histories** and **response spectra** of the acceleration

History/State of the art



- Considerable boost to the research and engineering application since the early 70s, with the development of **theoretical formulations** (vertical wave propagation in horizontally layered visco-elastic materials; Roesset 1977) and first **numerical approaches** (equivalent linear visco-elastic method; Schnabel *et al*. 1972)
- Application to two- and three-dimensional cases for the study of **topographic effects** (buried valleys/hills; King and Tucker 1984, Geli *et al*. 1988)
- Influence of the **aleatory variability** of the soil dynamic properties and input motion (Field and Jacob 1993, Roblee *et al*. 1996)
- Analysis of the **epistemic uncertainty** of the results due to the adopted numerical approach (Kaklamanos *et al*. 2015, Zalachoris and Rathje 2015)

Ground response analysis

History/State of the art

- Despite all this, there are still fundamental questions to be answered:

  Total stress *vs* effective stress analysis

  Evaluation of the **soil dynamic properties** (i.e. stiffness degradation and hysteretic damping) at very small and large shear strains

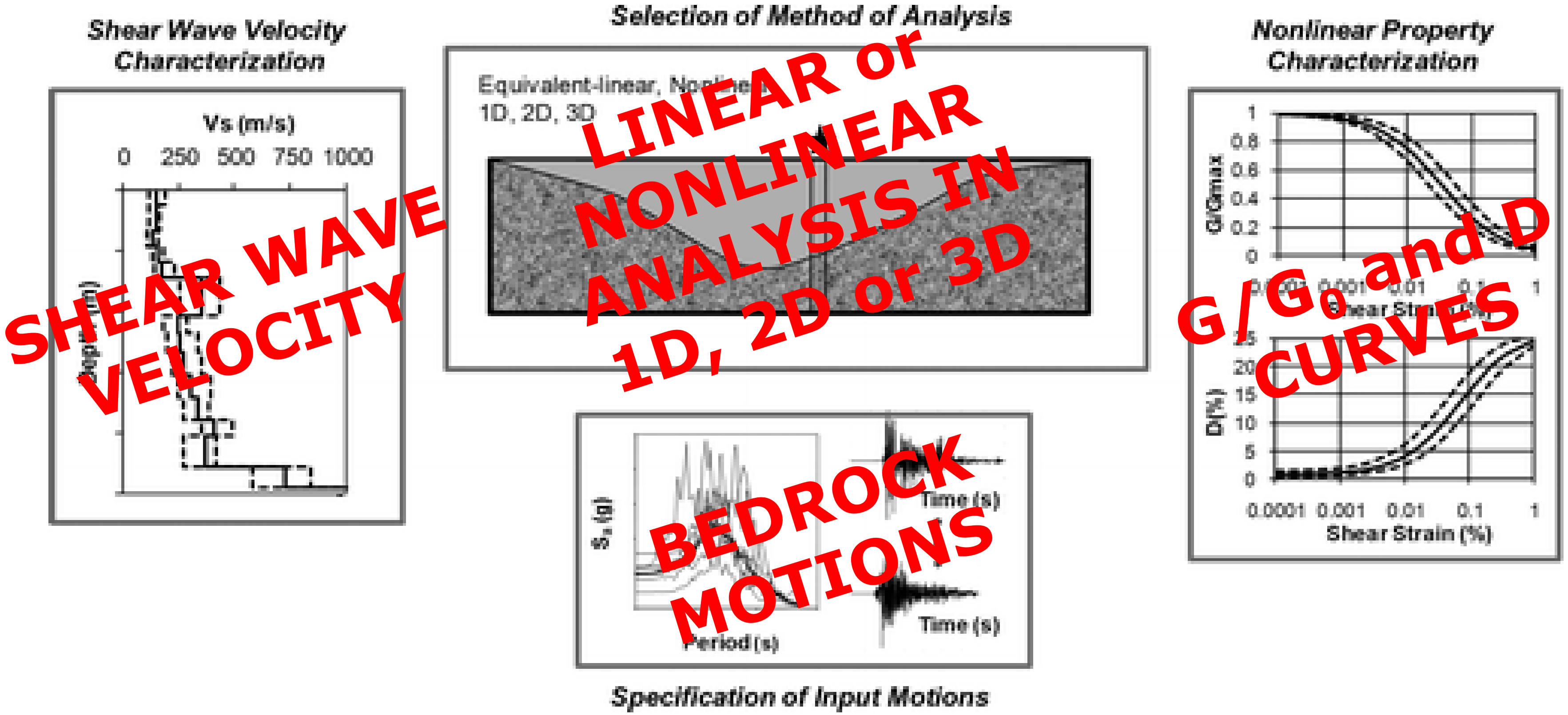
  Influence of **multi-directional loading** conditions on the mechanical behaviour of soils (for 3D simulations)

  Capabilities of advanced elasto-plastic constitutive models (e.g. multi-surface, bounding surface) to **predict the cyclic response of soils**

→ Crucial importance of down-hole accelerometer arrays in well-investigated sites for the **validation of numerical methods** (ESG-IASPEI/IAEE 1992, ESG-IASPEI/IAEE 2006, Turkey Flat 2008, E2VP 2010, PRENOLIN 2013)

Ground response analysis

Sources of **variability/uncertainty** in site response analyses



from Rathje *et al*. 2010

Ground response analysis

PREdiction of NOn-LINear soil behavior (**PRENOLIN**) was an **international benchmark** aiming to test multiple numerical simulation codes that are capable of predicting nonlinear seismic site response with various constitutive models

The benchmark involved **21 teams** (including POLIBA) and **23 different** numerical **codes**

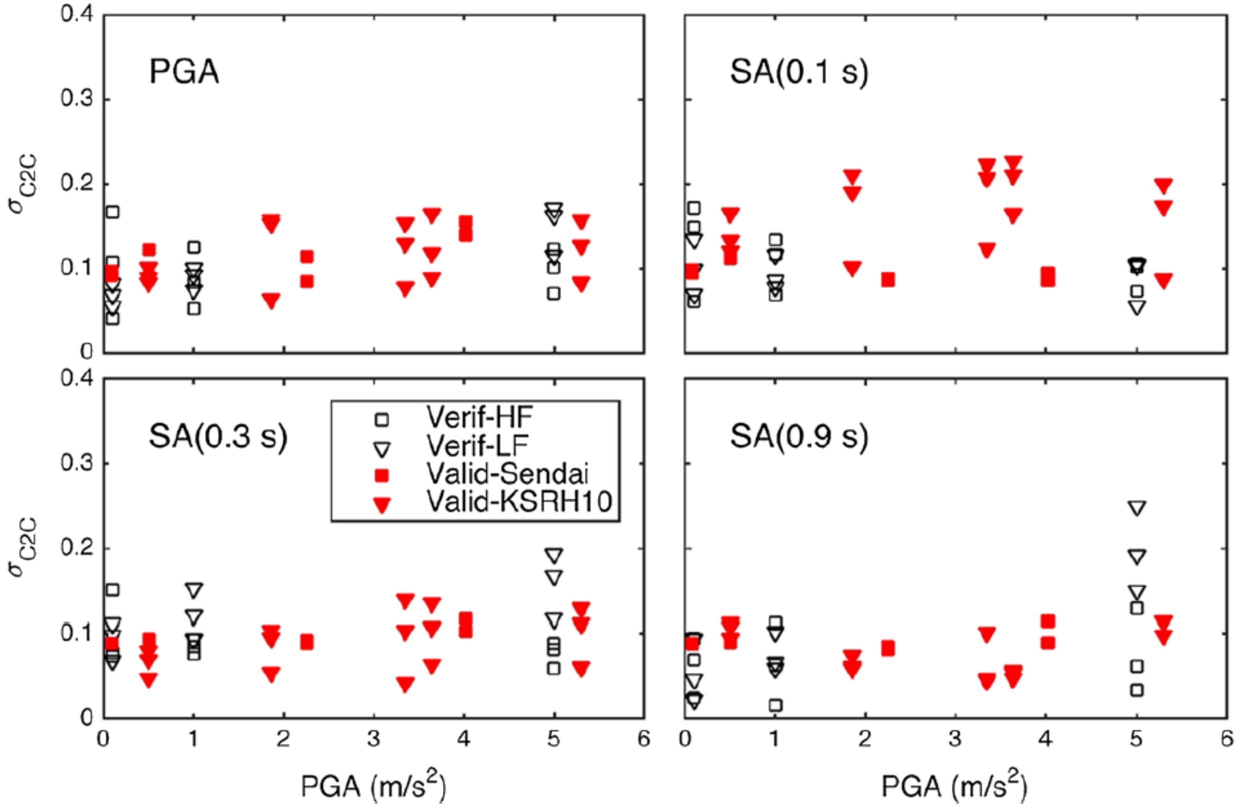
During the validation phase, two sites were studied, i.e. KSRH10 and Sendai, of the Japanese strong-motion networks KiK-net and Port and Airport Research Institute (PARI), respectively, with a pair of accelerometers at surface and depth

The **epistemic uncertainties** related only to wave propagation modeling using **different nonlinear constitutive models** are shown to increase with the strain level and to reach values around 0.2 (in log10 scale) for a peak ground acceleration of 5 m/s^2 at the base of the column, which may be reduced by almost 50% when the various models used the same shear strength and damping implementation

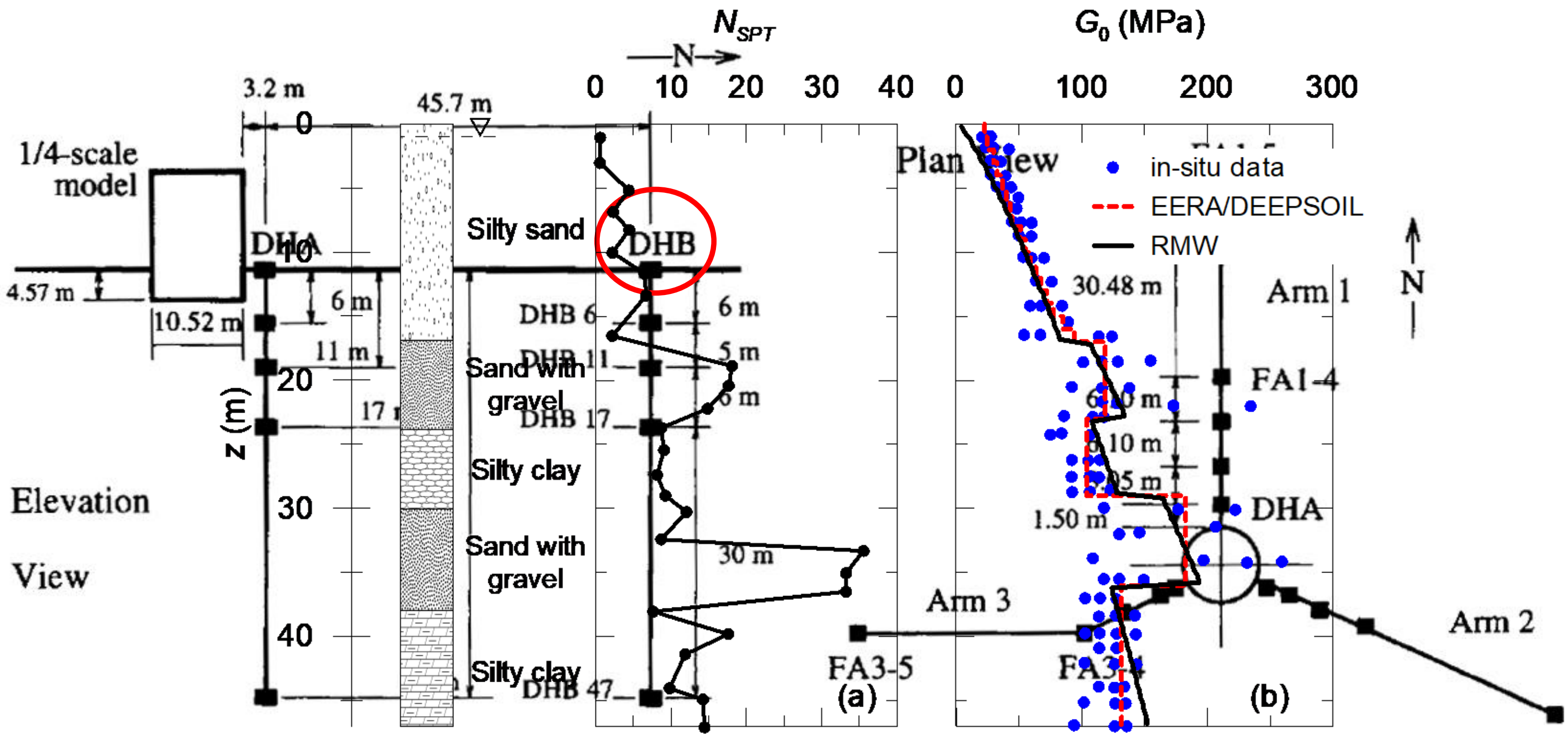
Régnier *et al*. (2018), PRENOLIN: International Benchmark on 1D Nonlinear Site-Response Analysis - Validation Phase Exercise, *Bulletin of the Seismological Society of America*, 108(2):876–900

Ground response analysis

It is found that the **code-to-code variability** given by the standard deviation of the computed surface-response spectra is around 0.1 (in log10 scale) regardless of the site and input motions. This indicates a <u>quite large influence of the numerical methods on site-effect assessment and more generally on seismic hazard</u>

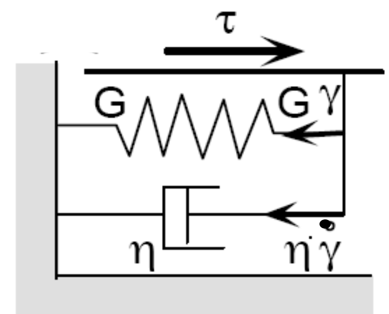


Influence of the adopted **numerical approach/constitutive law** on the prediction of site response at the LSST site in Lotung (Taiwan)

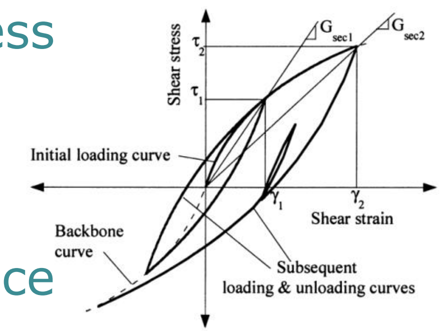


Elia G., Rouainia M., Karofyllakis D., Guzel Y. (2017), Modelling the non-linear site response at the LSST downhole accelerometer array in Lotung, *Soil Dynamics and Earthquake Engineering*, 102:1-14

The site response was studied adopting:

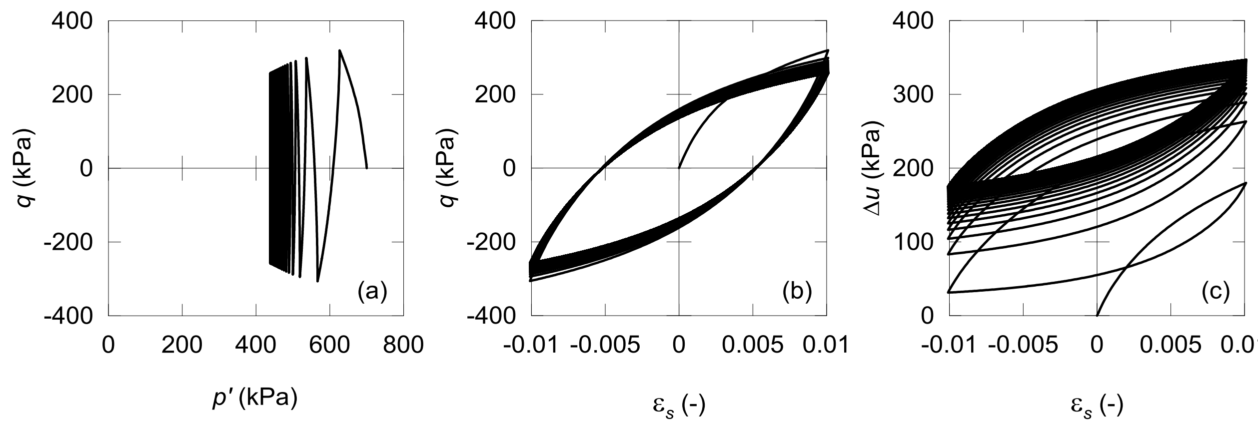


EERA (Bardet *et al*. 2000) = frequency-domain total stress analysis with the visco-elastic model

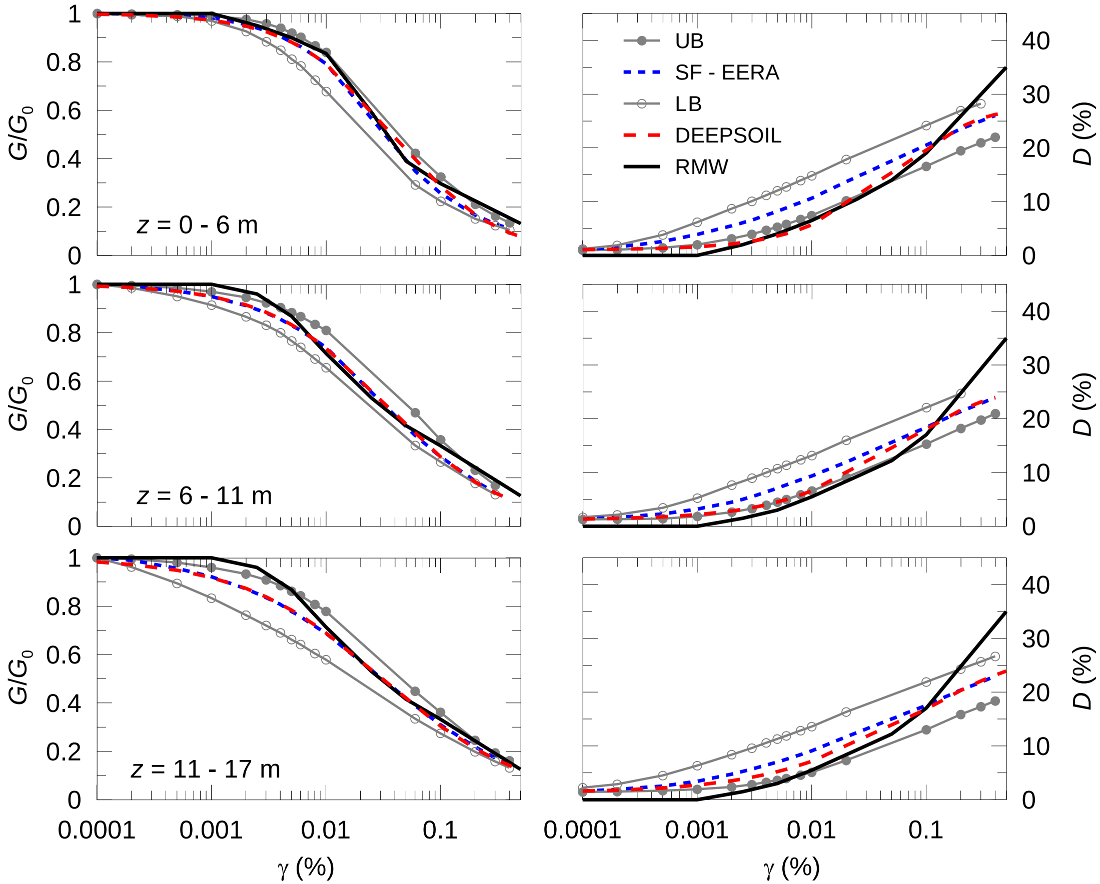


DEEPSOIL (Hashash 2005) = time-domain total stress analysis with the hyperbolic model

SWANDYNE (Chan 1995) with the **RMW** multi-surface model (Rouainia and Muir Wood 2000)



The different constitutive models were calibrated against the same set of laboratory and in-situ data

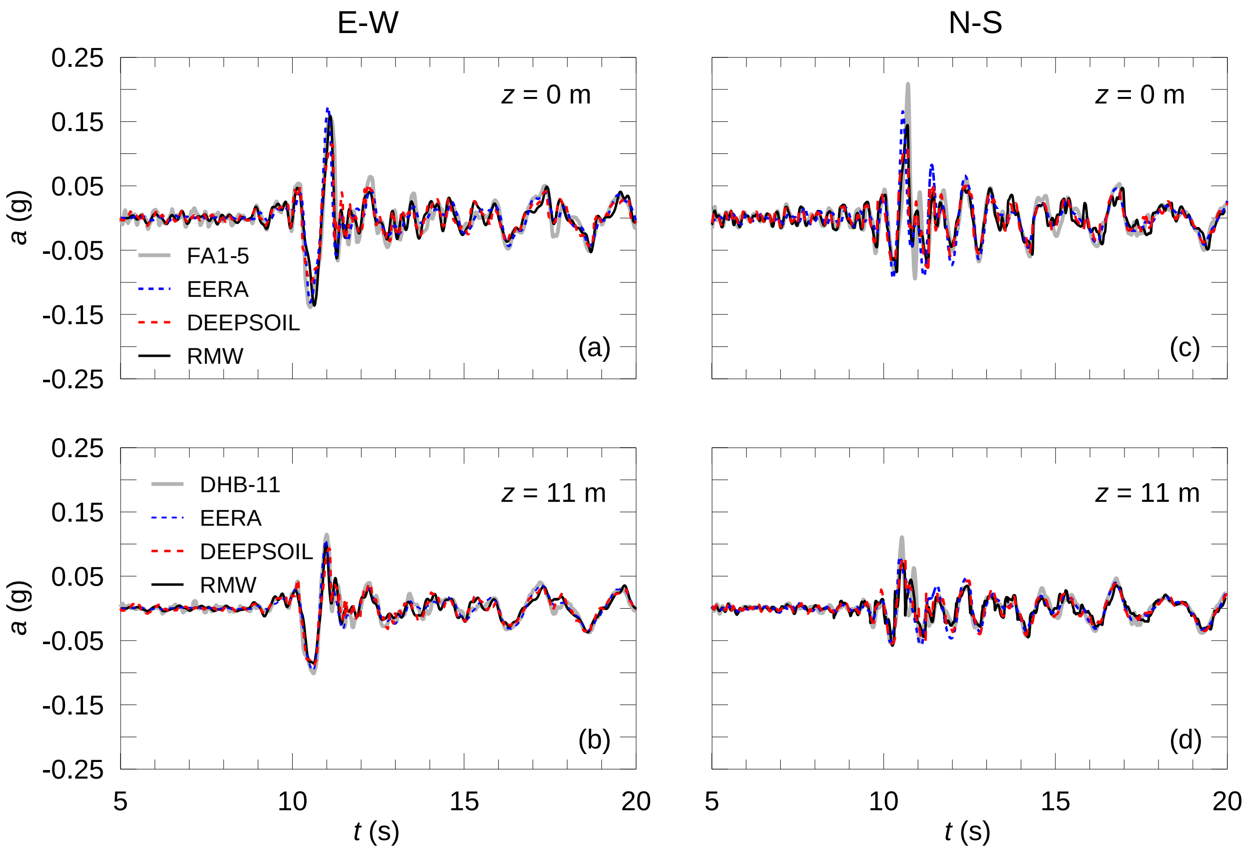


The free-field response was studied during one strong motion (LSST07) and one weak motion (LSST11)

Ground response analysis

Results for the LSST07 event (strong motion)

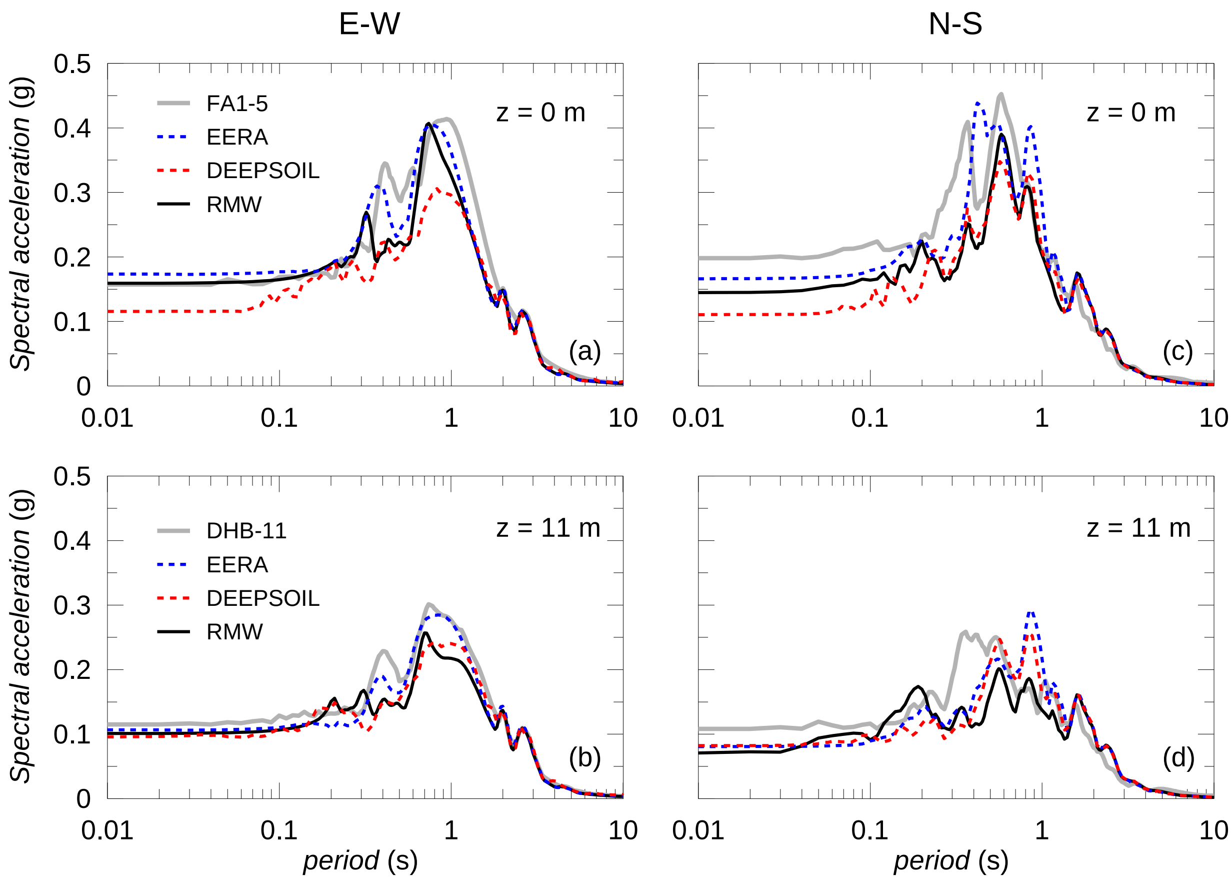
Comparison between numerical predictions obtained at two different depths and recorded data in terms of acceleration time histories



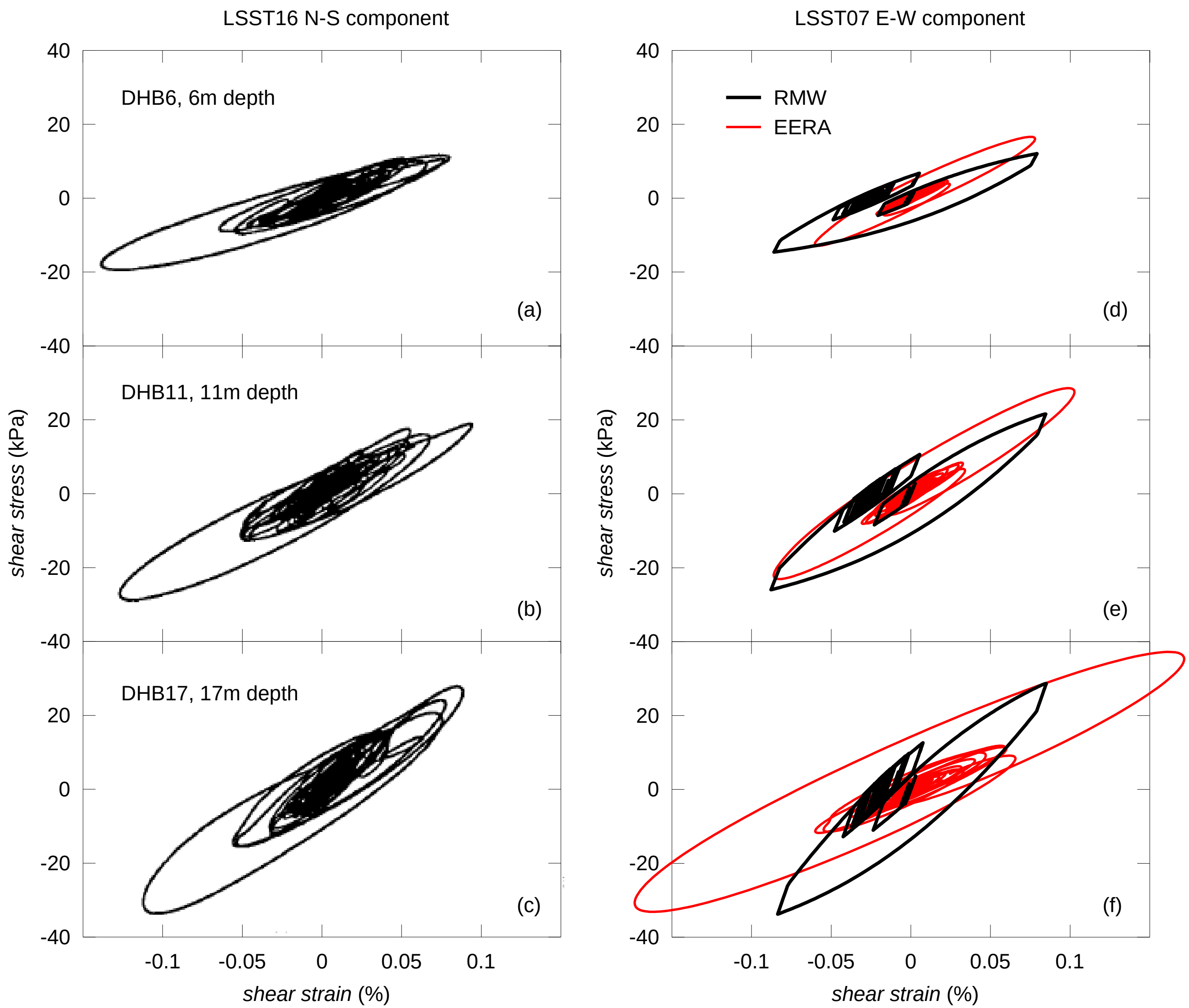
Ground response analysis

Results for the LSST07 event (strong motion)

Comparison between numerical predictions obtained at two different depths and recorded data in terms of response spectra



Ground response analysis



Ground response analysis

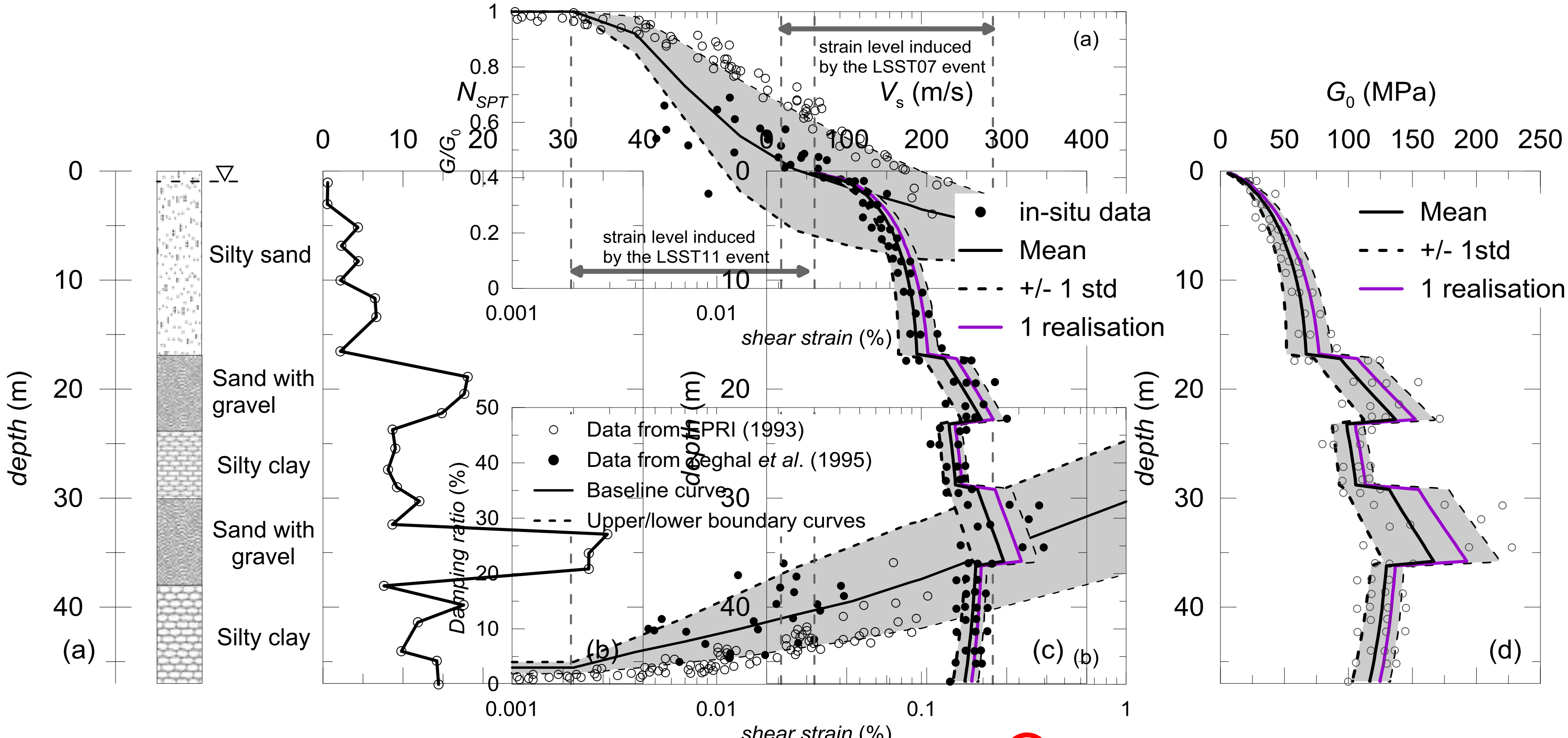
…some conclusions

✓The equivalent linear visco-elastic method **cannot capture** the frequency content and peak acceleration of the strong intensity event, due to its well-known limitations in the prediction of the soil nonlinear cyclic behaviour at large shear strains

✓The effective stress based predictions obtained with the advanced elasto-plastic RMW model are, instead, particularly **successful**

Ground response analysis

Influence of the **aleatory variability** of the soil dynamic properties on the site response prediction at Lotung (Taiwan)



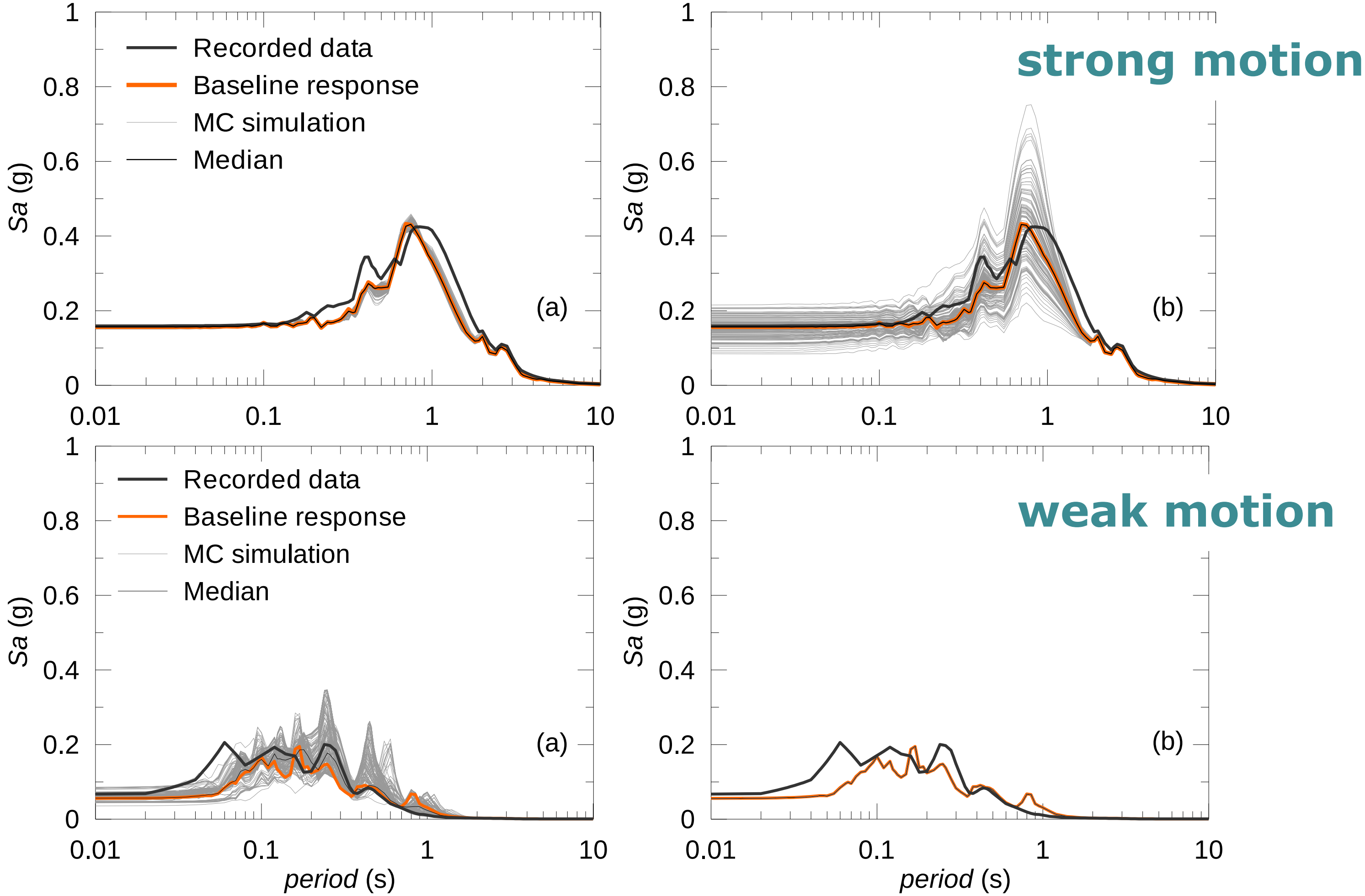
$$\frac{G_0}{p_r} = A\left(\frac{p_c}{p_r}\right)^n OCR^m$$

$$H = H_c = A\left(\frac{Bp_c^3}{(\lambda^* - \kappa^*)R}\right)\left(\frac{b}{b_{max}}\right)^{\psi}$$

Viggiani and Atkinson (1995)

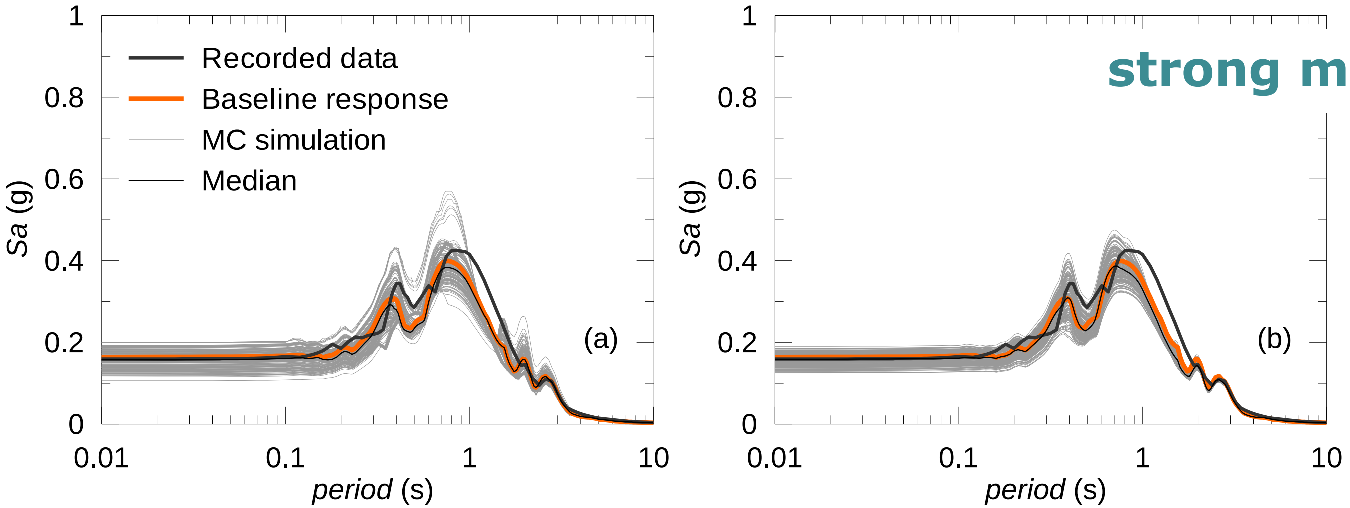
Ground response analysis

Influence of (a) initial stiffness profile, (b) nonlinear curves variability on the site response prediction using **the advanced numerical approach** (SWANDYNE with RMW)



Influence of (a) initial stiffness profile, (b) nonlinear curves variability on the site response prediction using **the equivalent linear visco-elastic approach** (EERA)

strong motion



Guzel Y., Elia G., Rouainia M. (2020), The effect of soil properties variability on nonlinear site response predictions: application to the Lotung site, *Computers & Geotechnics* (accepted)

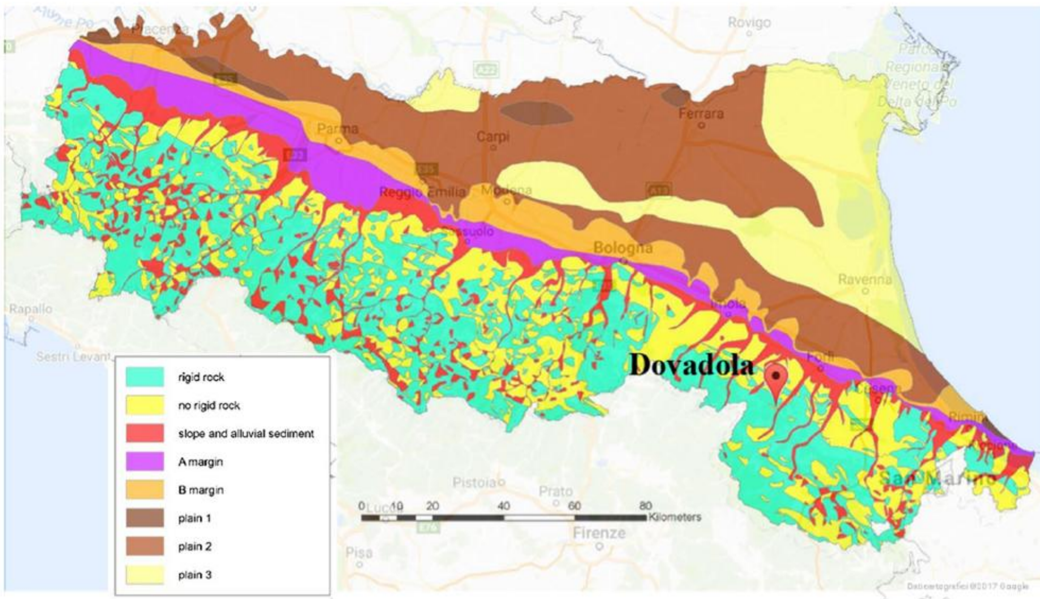
…some conclusions

✓The Monte Carlo simulations performed with the <u>advanced soil model</u> allow a **clear separation** between the effect of stiffness variability and that of soil nonlinear properties, depending on the seismic intensity of the input motion

✓The <u>equivalent linear visco-elastic approach</u>, instead, **is not able to distinguish** between the two effect, even in the case of the high intensity input motion

Examples of MS studies

Results of **II** and **III level** seismic microzonation studies for the Dovadola urban area (Forlì-Cesena, Emilia-Romagna)



Map of geo-lithological homogeneous area

H (m)	V_{SH} (m/s)									
	150	200	250	300	350	400	450	500	600	700
5	1.8	1.7	1.4	1.2	1.0	1.0	1.0	1.0	1.0	1.0
10	2.0	2.0	1.9	1.7	1.5	1.4	1.2	1.1	1.0	1.0
15	2.0	2.0	2.0	1.9	1.8	1.6	1.4	1.3	1.2	1.0
20	2.0	2.0	2.0	2.0	1.9	1.7	1.6	1.4	1.3	1.0
25	2.0	2.0	2.0	1.9	1.8	1.8	1.6	1.5	1.3	1.0
30		1.9	1.9	1.9	1.8	1.7	1.6	1.5	1.4	1.2
35		1.9	1.9	1.9	1.9	1.7	1.6	1.4	1.4	1.2
40		1.9	1.9	1.9	1.9	1.7	1.6	1.4	1.4	1.2
50		1.9	1.9	1.9	1.9	1.8	1.6	1.4	1.4	1.2

Regional chart for F_{PGA} *Appennino 1*

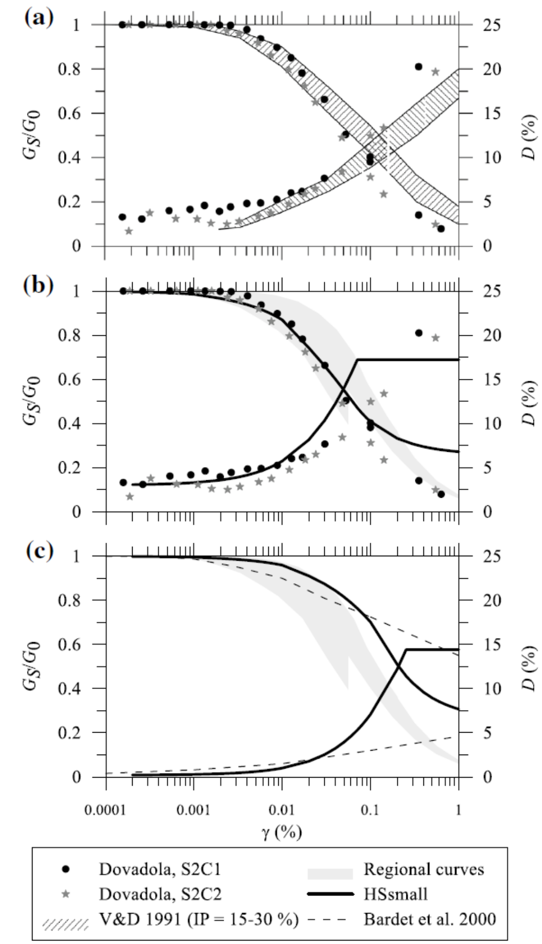
The Emilia-Romagna region published the first version of the regional charts (i.e. II level MS) in 2007 and then updated them in 2015

Falcone G., Boldini D., Martelli L., Amorosi A. (2020), Quantifying local seismic amplification from regional charts and site specific numerical analyses: a case study, *Bulletin of Earthquake Engineering*, 18:77–107

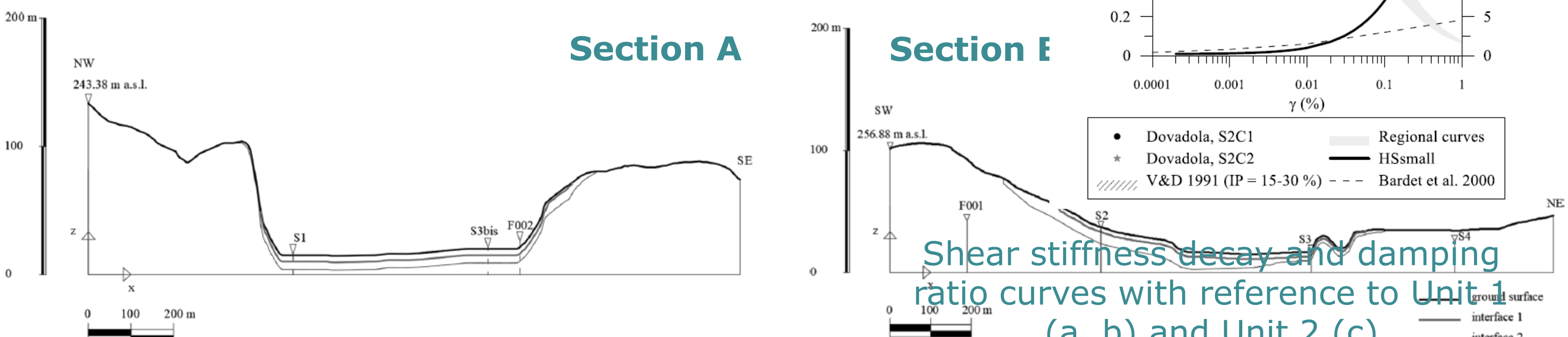
Examples of MS studies

The area was investigated by 33 continuous boreholes, 13 CPTs, 16 SPTs, 2 down-hole tests, 19 HVSR measurements and 5 MASWs; the assumed overall geological setting is that illustrated by the Geological Map of Italy SGI (2001), further validated in this study thanks to four additional boreholes and three down-hole tests

Geotechnical unit	V_{S_mean} (m/s)	γ (kN/m^3)	IP (%)	$G(\gamma)/G_0$, $D(\gamma)$ (–)
1	350	21	18	Figure 5a, b
2	650	20	–	Figure 5c
3	800	20	–	–



Shear stiffness decay and damping ratio curves with reference to Unit 1 (a, b) and Unit 2 (c)



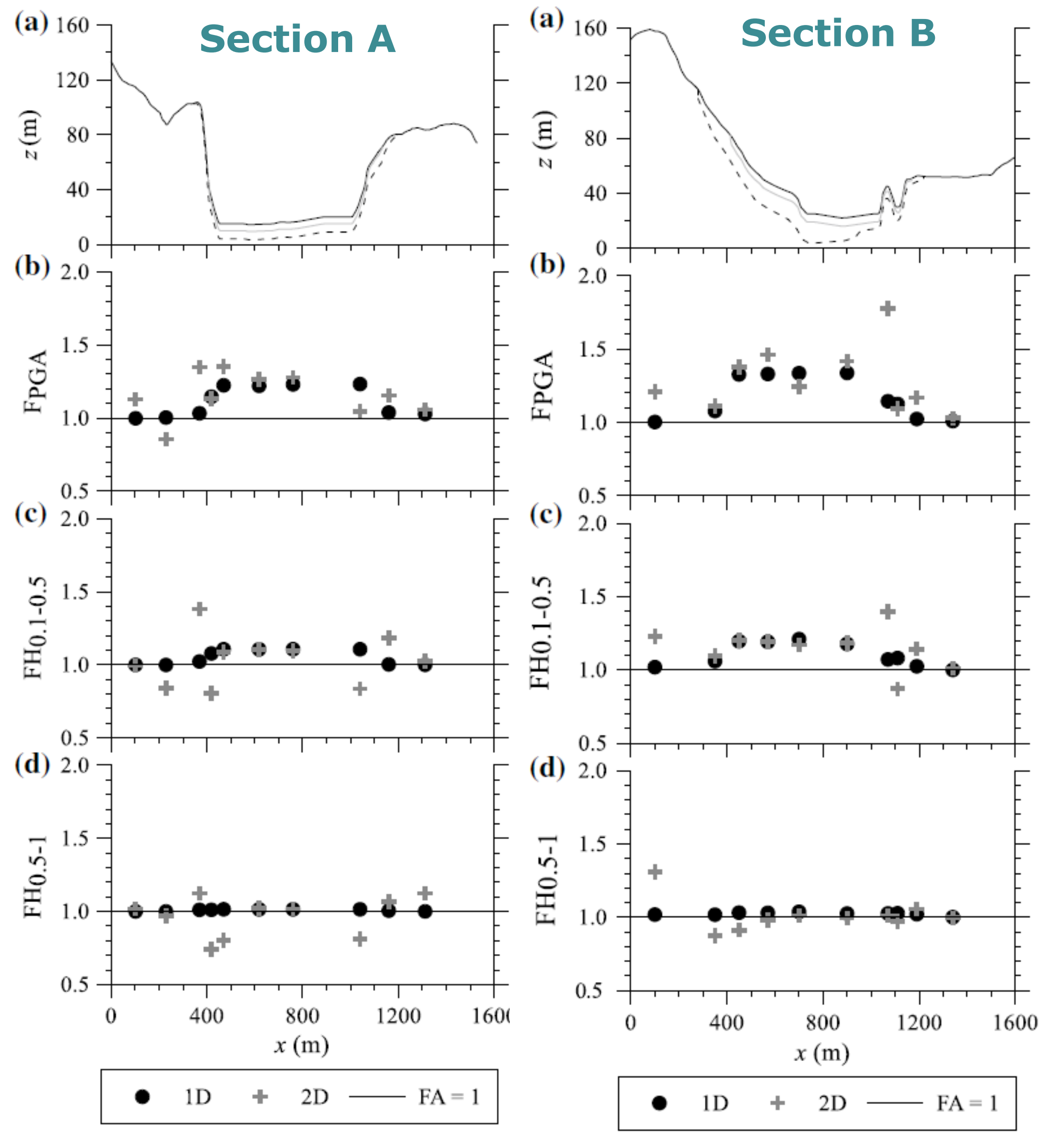
Investigated geotechnical sections

Examples of MS studies

AFs were determined by means of site specific seismic response numerical analyses, adopting both 1D and 2D schemes, and by the regional charts

- The AFs determined from the regional charts match well the corresponding AFs computed from 1D site specific analyses

- 1D and 2D simulations predict a very similar seismic response at the centre of the large valley, while not negligible 2D effects were observed at lateral sides of the valley and at the crest of outcropping rock, leading to significant discrepancies in terms of amplification factors between 1D (numerical and regional approaches) and 2D analyses



Examples of MS studies

- The topographical amplification predicted by the 2D site response analyses was well captured by the regional procedure in presence of outcropping rock

- Instead, when coupled phenomena prevail, due to both irregular sub-interface and uneven ground surface, the simplified regional approach reveals its limitations making necessary to approach the analysis by a more complex, thus more time consuming, multi-dimensional seismic response analyses

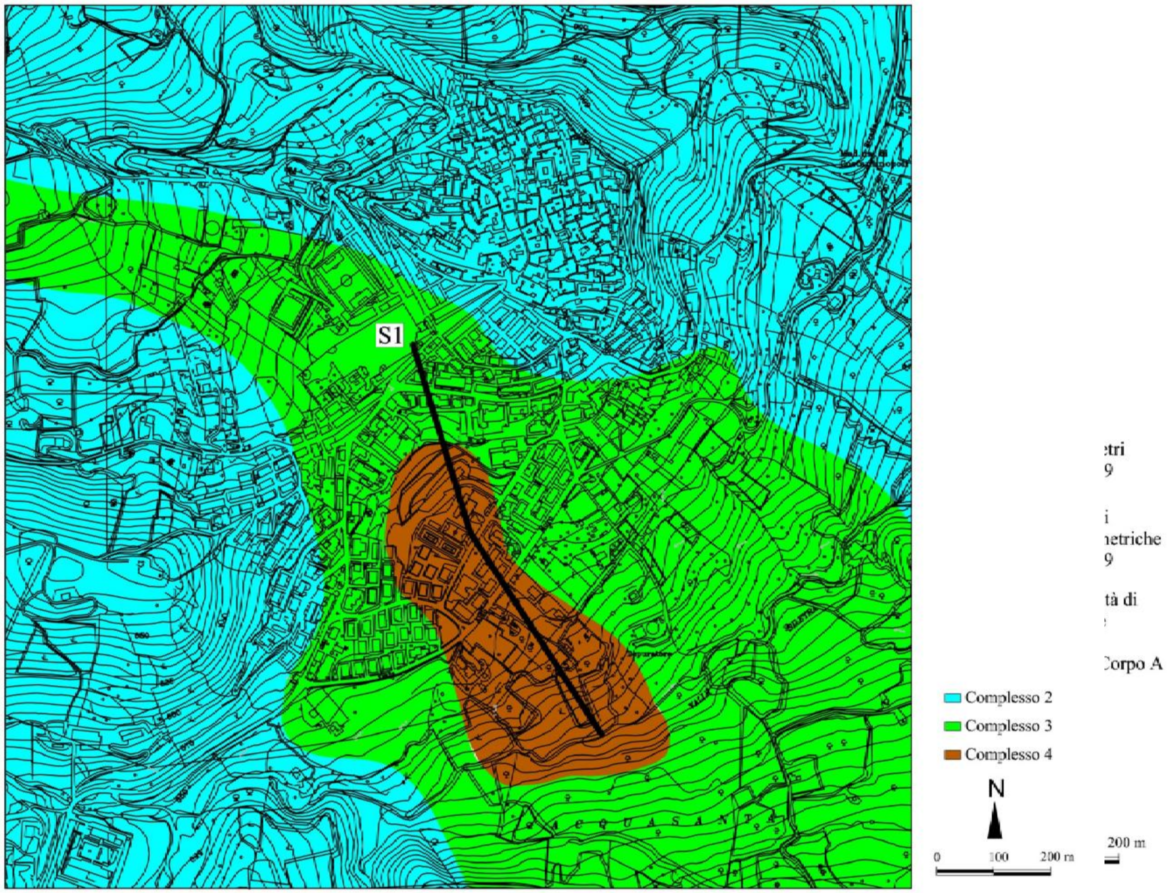
Section A

x (m)	Regional charts			Numerical
	F_{PGA} (–)	S_T (–)	$S_T \cdot F_{PGA}$ (–)	F_{PGA} (–)
370	1.00	1.31	1.31	1.35
1054	1.20	1.00	1.20	1.04

Section B

x (m)	Regional charts			Numerical
	F_{PGA} (–)	S_T (–)	$S_T \cdot F_{PGA}$ (–)	F_{PGA} (–)
145	1.00	1.00	1.00	1.21
1069	1.20	1.32	1.58	1.78
1149	1.10	1.13	1.24	1.10

Results of a **III level** seismic microzonation study for the Bovino urban area (Foggia, Puglia)



MOPS map from the I level study (Palladino 2001)

Geotechnical map adopted in the III level study

The assumed overall geological setting is that proposed by Petti (2010), Cotecchia *et al*. (2016) and Santaloia *et al*. (in prep.)

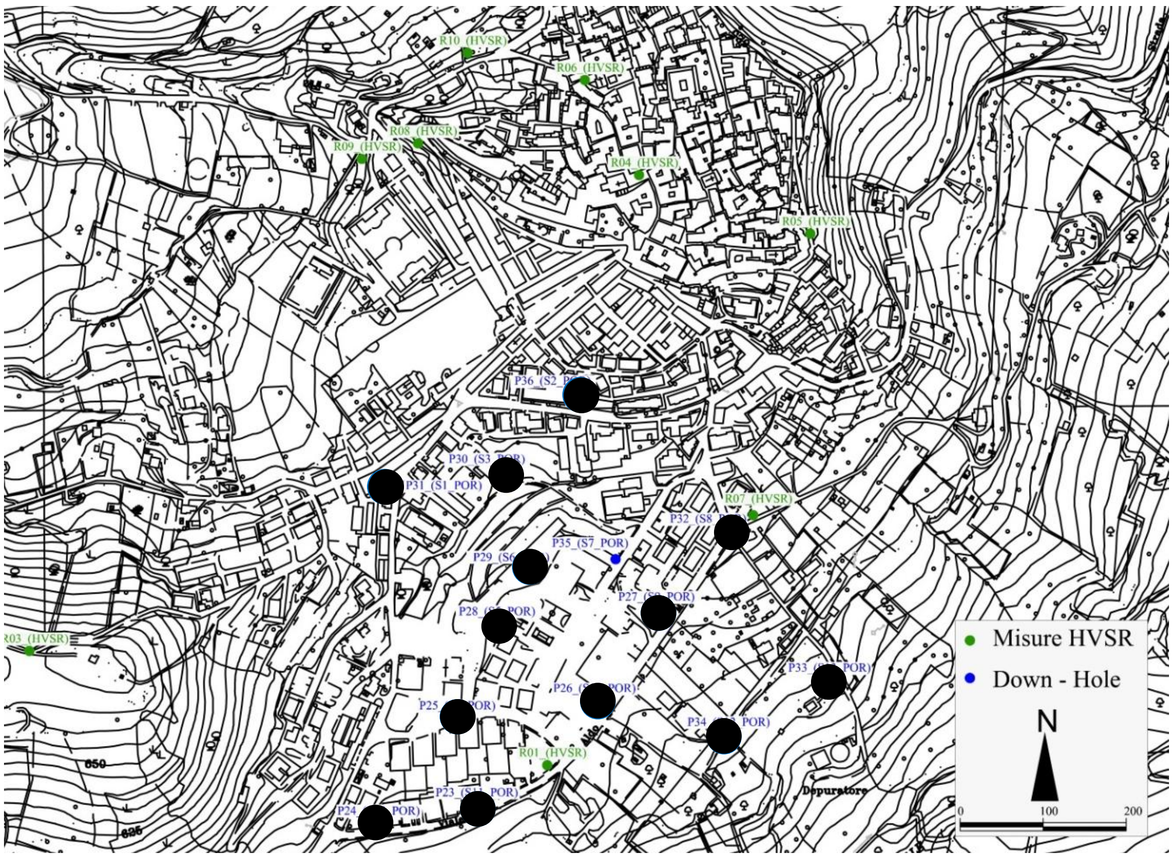
The same Authors also pointed out the presence of landslide phenomena in the same area

This has been accounted for though the evaluation of the seismic induced displacements using the Newmark rigid block analysis

Falcone G., Boldini D., Amorosi A. (2018), Site response analysis of an urban area: A multi-dimensional and non-linear approach, *Soil Dynamics and Earthquake Engineering*,109:33–45

Examples of MS studies

The geological model was based on the information derived from 12 continuous coring boreholes, 10 to 40 m deep, 8 shear wave velocity profiles, determined by means of down-hole prospections, and 8 measurements of horizontal to vertical spectral ratio. Moreover, 32 undisturbed soil samples were collected during the borehole drilling.



● 13 Sondaggi

9 Down-hole

32 Campioni indisturbati

7 misure HVSR

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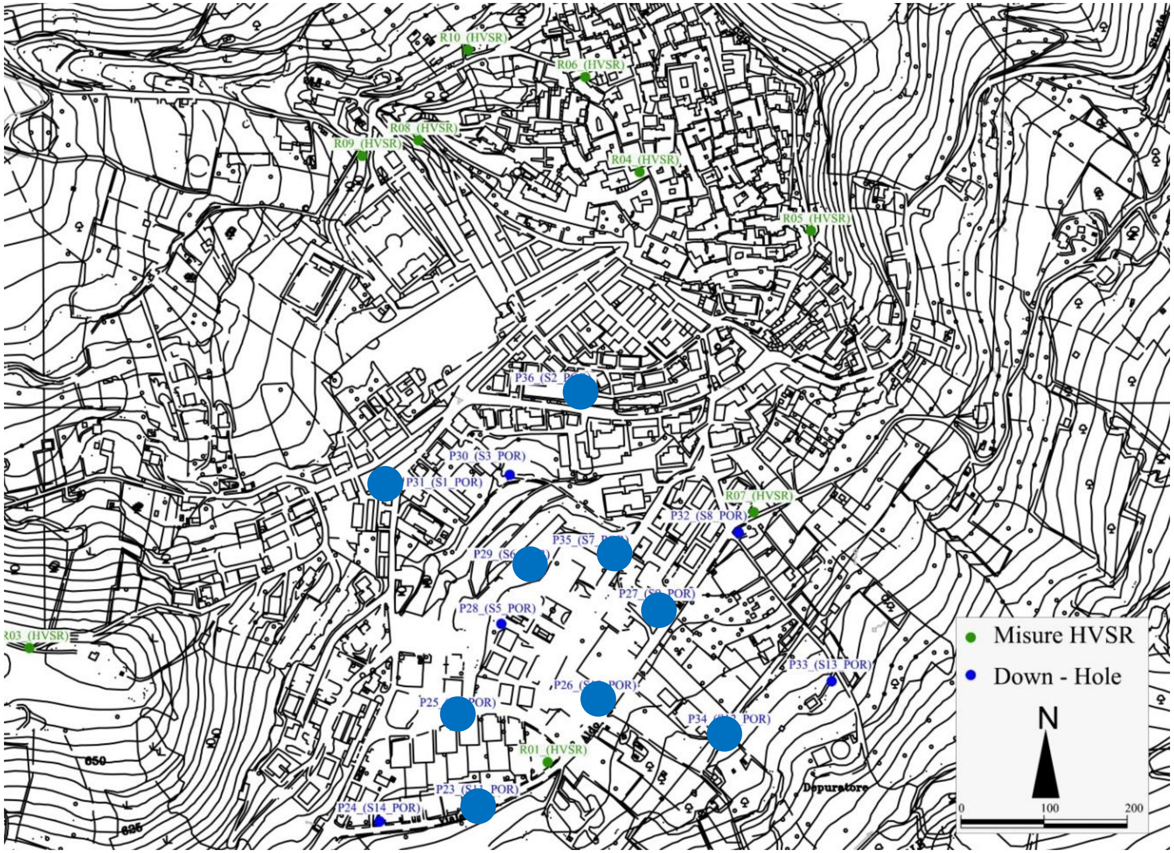

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12 Sondaggi

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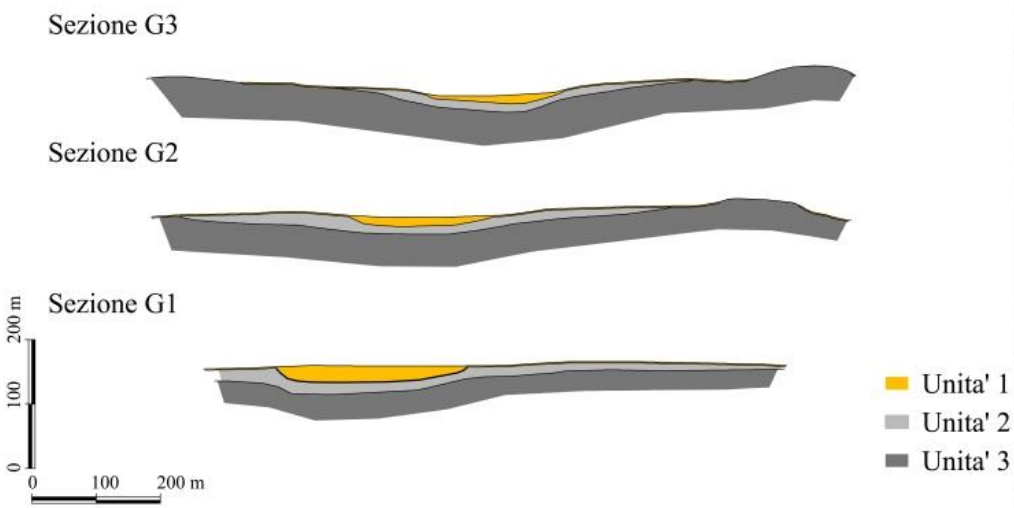
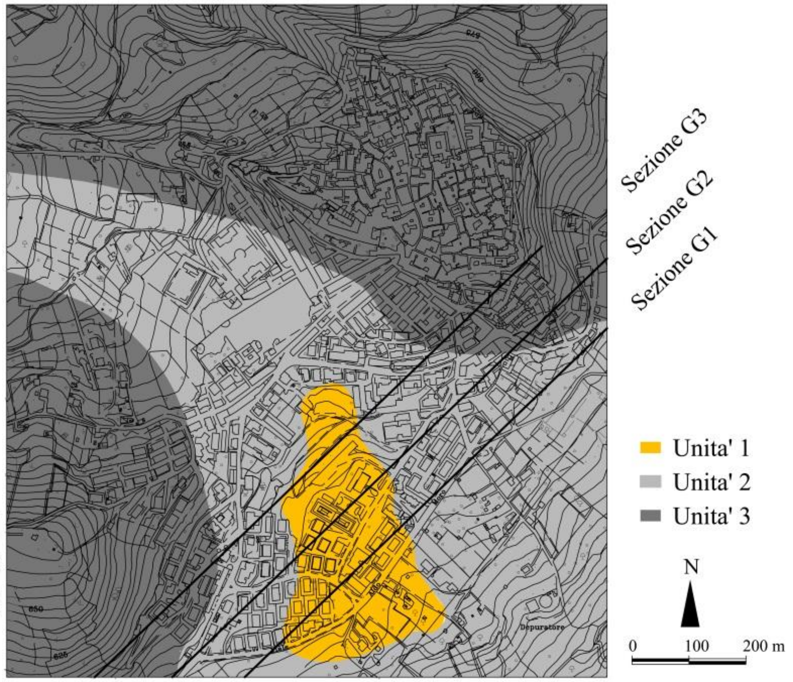
Examples of MS studies

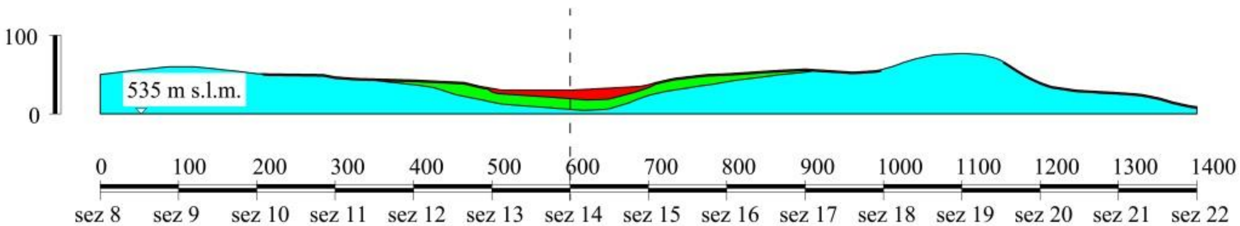
The geotechnical model was derived from the geological one by comparing boreholes and V_S logs to highlight strata characterized by the same mechanical behaviour (Falcone 2017). It results in three geotechnical units characterised by a constant value of the shear wave velocity with depth.

Unità geologica	Unità geotecnica	γ_{sat} (kN/m^3)	V_S (m/s)	ν	IP (%)
V1, W1[1]	1	18	200	0.25	22
W1[2]	2	18	800	0.25	22
FAE, BOV	3	18	1200	0.25	/

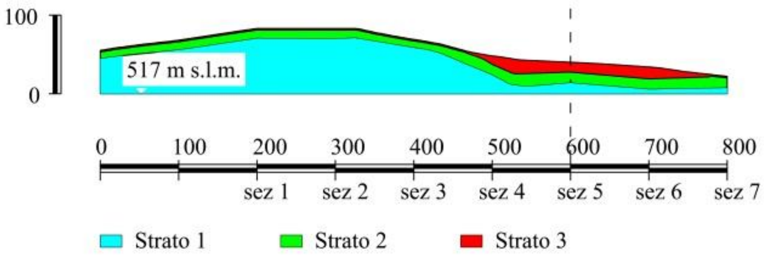


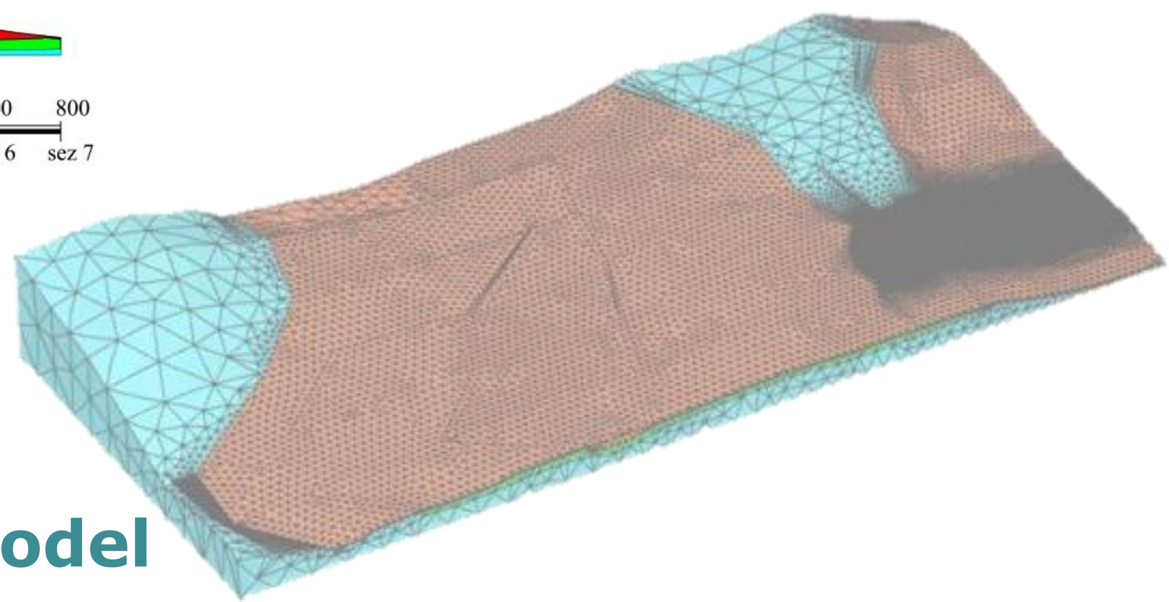


The numerical simulations were carried out in the time-domain by the FE codes QUAKE/W and PLAXIS adopting 1D and 2D geometrical schematizations. Additional 3D analyses were also performed using the code PLAXIS.



2D models





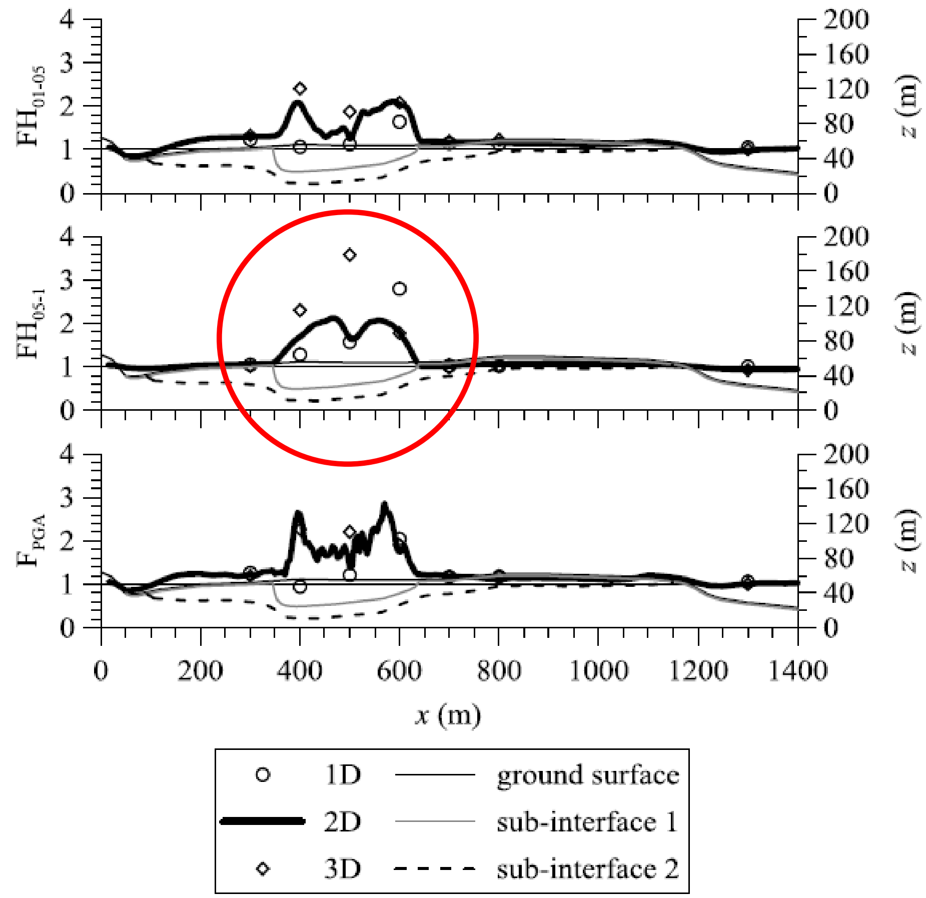
3D model

Examples of MS studies

- The predicted signals at the ground surface result amplified in the valley and hill areas and slightly de-amplified at the toes of the hill

- The amplification pattern found for the shallower and narrower portion of the valley seems to be only affected by the local stratigraphic conditions, since the 1D, 2D and 3D simulations provided very similar results

- Where the valley is deeper and larger, the 3D approach predicted a seismic amplification that is about twice than that predicted by 1D and 2D schemes in the period range 0.5<*T*<1s



Again, the amplification factors were found to strongly depend on the adopted geometrical scheme!

Conclusions and future perspectives

- ✓ The work done so far by the DPC has established a **common working method** and **language**
- ✓ The three level approach for MS studies involves **different degrees of expertise** and **knowledge**, thus requiring the input of experts from different technical-scientific background
- ✓ Ground response analyses are the foundation for Level II and III MS studies
- ✓ The amplification at ground surface is **strongly dependent** on the adopted geometrical scheme, numerical approach and constitutive hypothesis
- ✓ The research has shown how advanced multi-dimensional numerical analyses can **help to understand** the seismic response of an area characterised by complex geology and irregular ground surface and their use **should be promoted** for technical applications

La risposta sismica locale a supporto della microzonazione sismica

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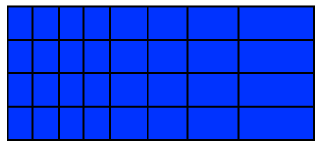
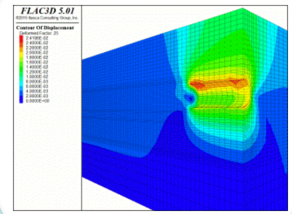
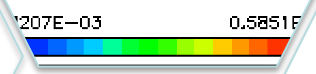
*Professore Associato di Geotecnica
presso il DICATECh del Politecnico di Bari

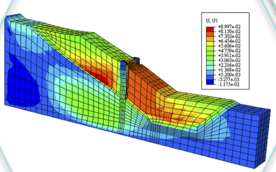
Politecnico di Bari Newcastle University IRPI GEO TECH



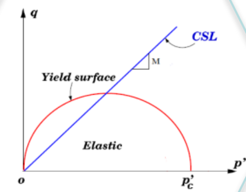


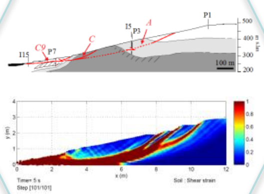
Fondazioni





Geotecnica computazionale





Stabilità dei pendii

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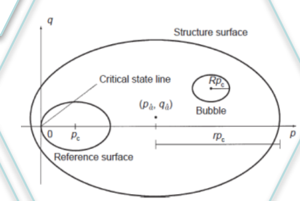
Modellazione costitutiva



Geotecnica sismica