



Assessing Nonlinear Behavior of Soils in Seismic Site Response: Statistical Analysis of KiK-net Strong-Motion Data

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Introduction

Non-linear soil behaviour: strong impact on site response

1- Example with Tohoku recordings

Even for moderate events:

2- Statistical analysis on all KiK-net sites

What are the effects on site response?

What are the pertinent parameters to predict such behavior?

3- Statistical analysis on 54 KiK-net sites

→ Need to take this phenomenon into account

Especially in low seismicity areas?

Numerical simulations. But, first we need site characterization/ expensive tests:

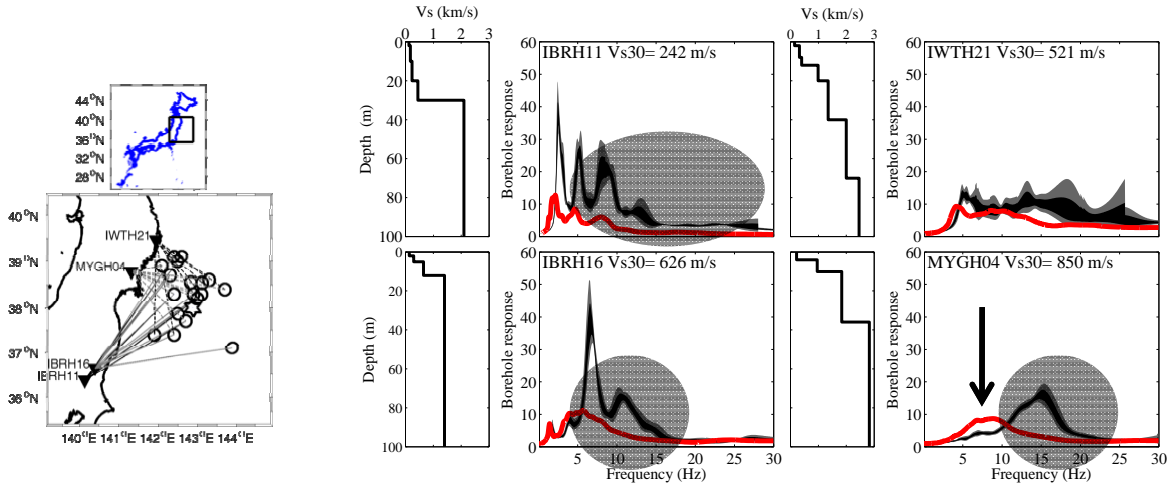
What is the depth until which this characterization is required ?

4- Inversion of non-linear site response

1- Example with Tohoku recordings

Non-linear soil behaviour : strong impact on site response

- Comparison of site responses (Fourier spectral ratios on borehole data)
- Tohoku main event versus aftershocks at 4 KiK-net sites

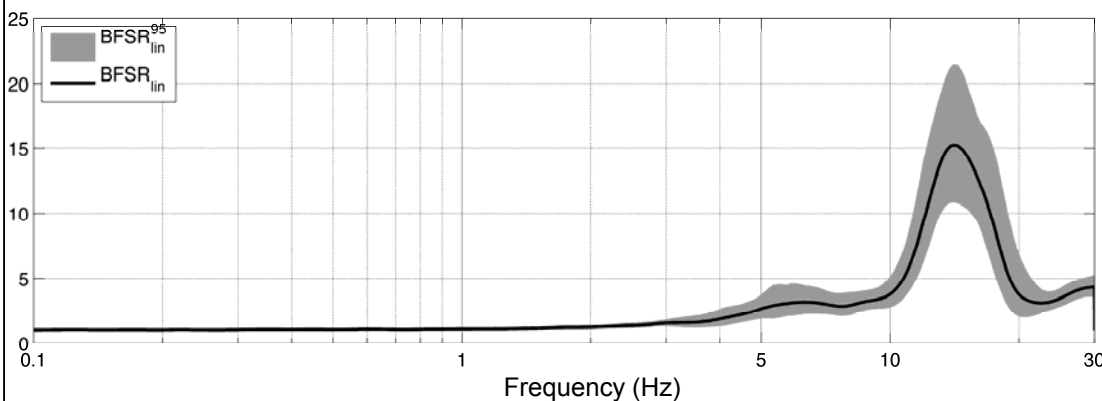


- Shift of the amplification peak toward low frequencies
→ Increase amplification at low frequencies !!!
- Decrease of the amplification at high frequencies

2- Statistical analysis on all KiK-net sites

Non-linear soil behaviour : strong impact on site response even for moderate events

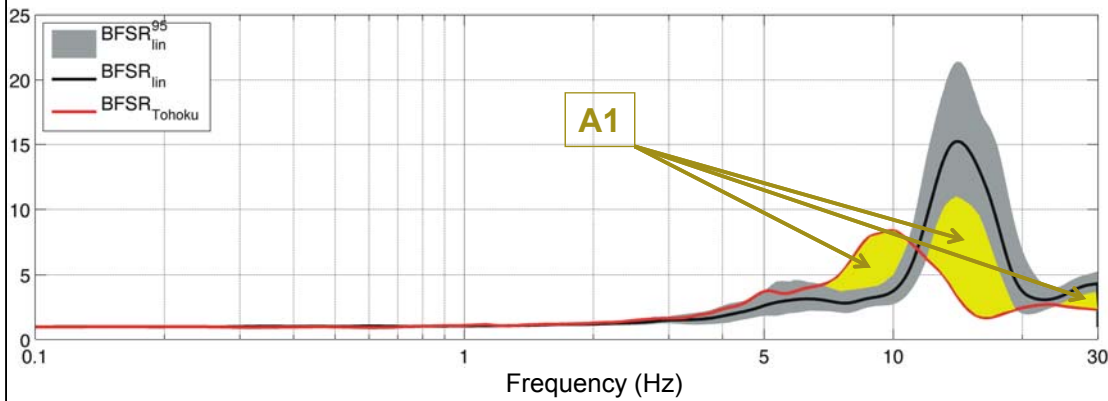
- Comparison of site responses (Fourier spectral ratios on borehole data)
- For all events we calculated: PNL_{ev} (%) Percentage of non-linearity:



2- Statistical analysis on all KiK-net sites

Non-linear soil behaviour : strong impact on site response even for moderate events

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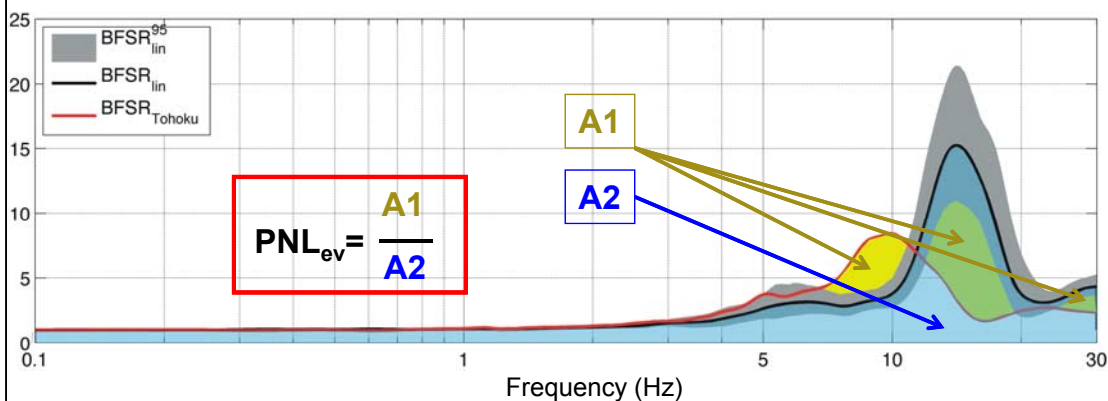


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2- Statistical analysis on all KiK-net sites

Non-linear soil behaviour : strong impact on site response even for moderate events

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2- Statistical analysis on all KiK-net sites

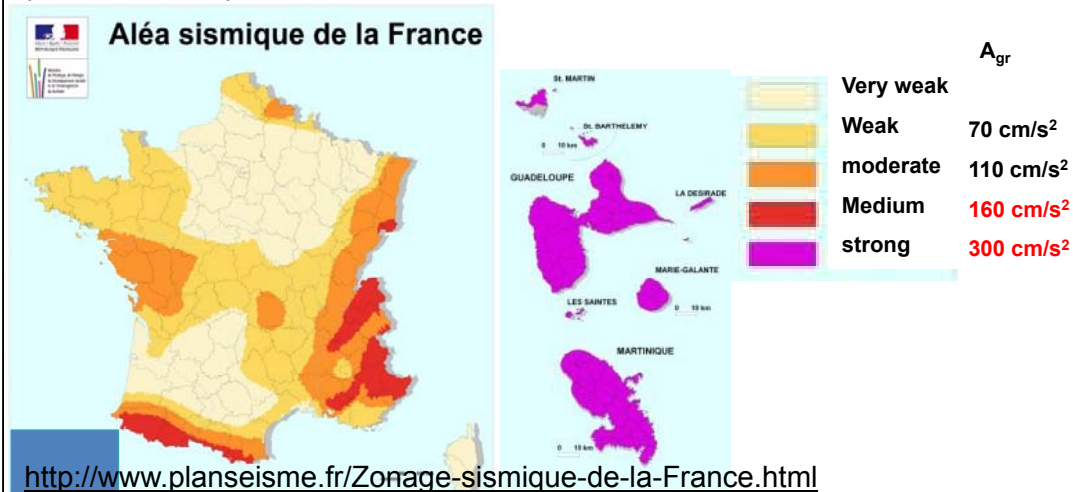
Probability $P_{NLev} > 10\%$: $NL \neq$ linear site response ?

$PGA > 75 \text{ cm/s}^2$ at depth \approx $PGA > 150 \text{ cm/s}^2$ at the surface

$P \geq 40\%$ Whatever the site!!

Probability of having large modification linear/non-linear site response is high even for moderate EQ

French seismic zonation
(22 octobre 2010)



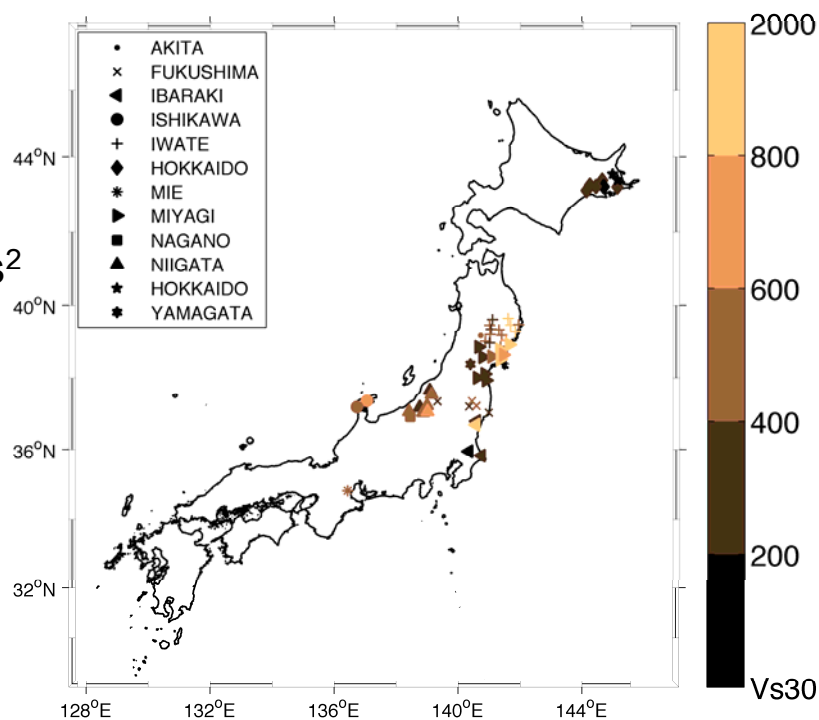
3- Statistical analysis on 54 KiK-net sites

Sites selection

- 54 sites

- 2 EQ
 $PGA > 50 \text{ cm/s}^2$
(downhole)

- Variability
 V_{s30} OK



3- Statistical analysis on 54 KiK-net sites

Per site : definition of fNL

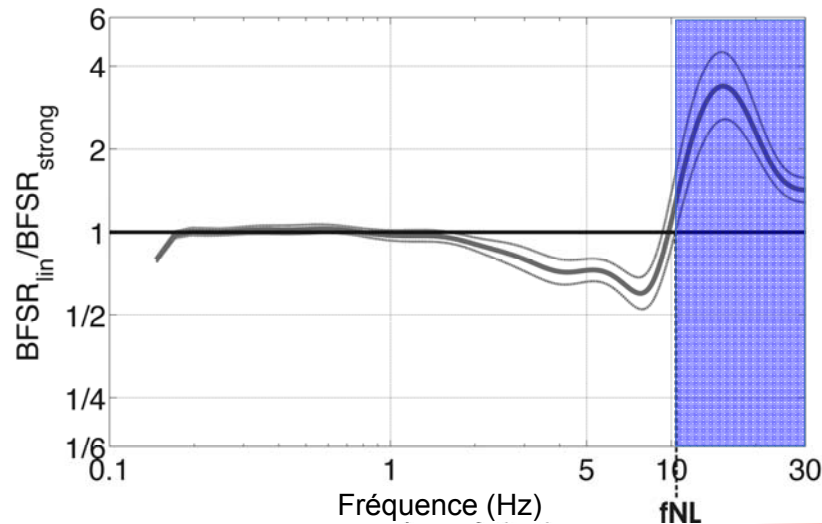
Linear to non-linear site response ratio

Field et al (1997)

fNL frequency from which the ratio is >1

f > fNL
 $BFSR_{lin} > BFSR_{strong}$

f < fNL
 $BFSR_{lin} < BFSR_{strong}$

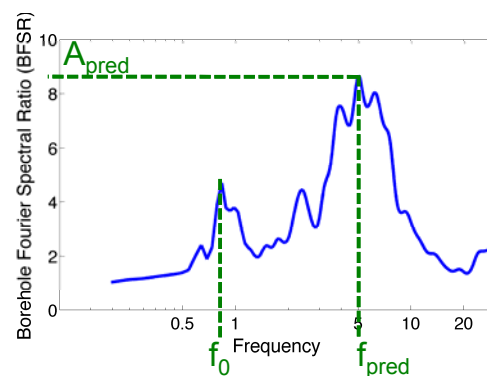


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3- Statistical analysis on 54 KiK-net sites

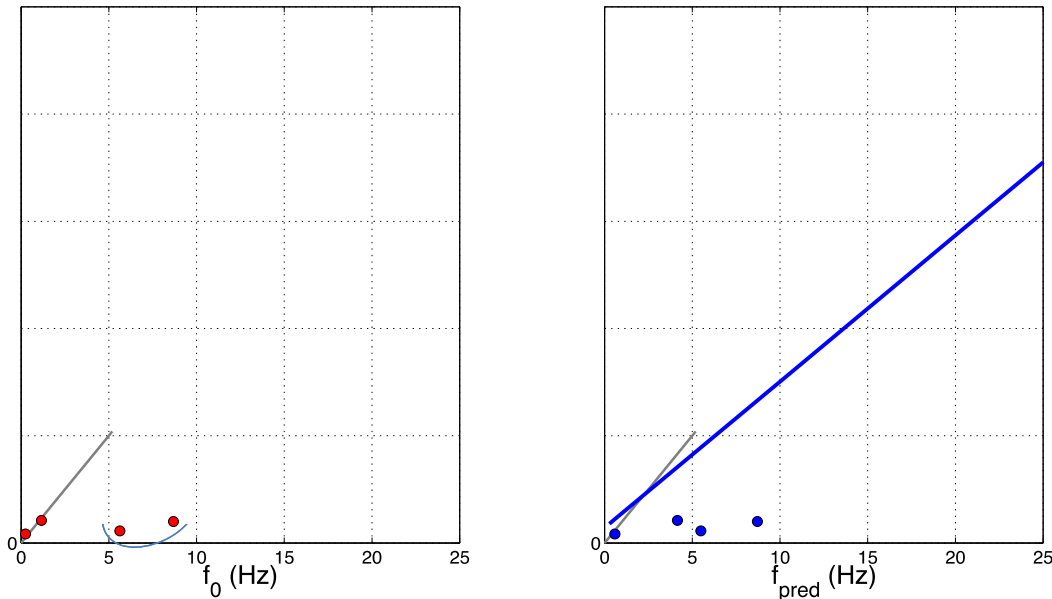
Correlation fNL with soil and site response parameters

- f_0 : Fundamental resonance frequency: H/V surface
- A_{pred} : Maximal amplitude of the mean linear site-response BFSR
- f_{pred} : Associated frequency to A_{pred}



3- Statistical analysis on 54 KiK-net sites

Correlation fNL with soil and site response parameters



fNL between f_0 et f_{pred} :

- HF more affected by NL soil behaviour
- NL takes mostly place in the soil layers linked to HF amplifications
- Shallow layers

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3- Statistical analysis on 54 KiK-net sites

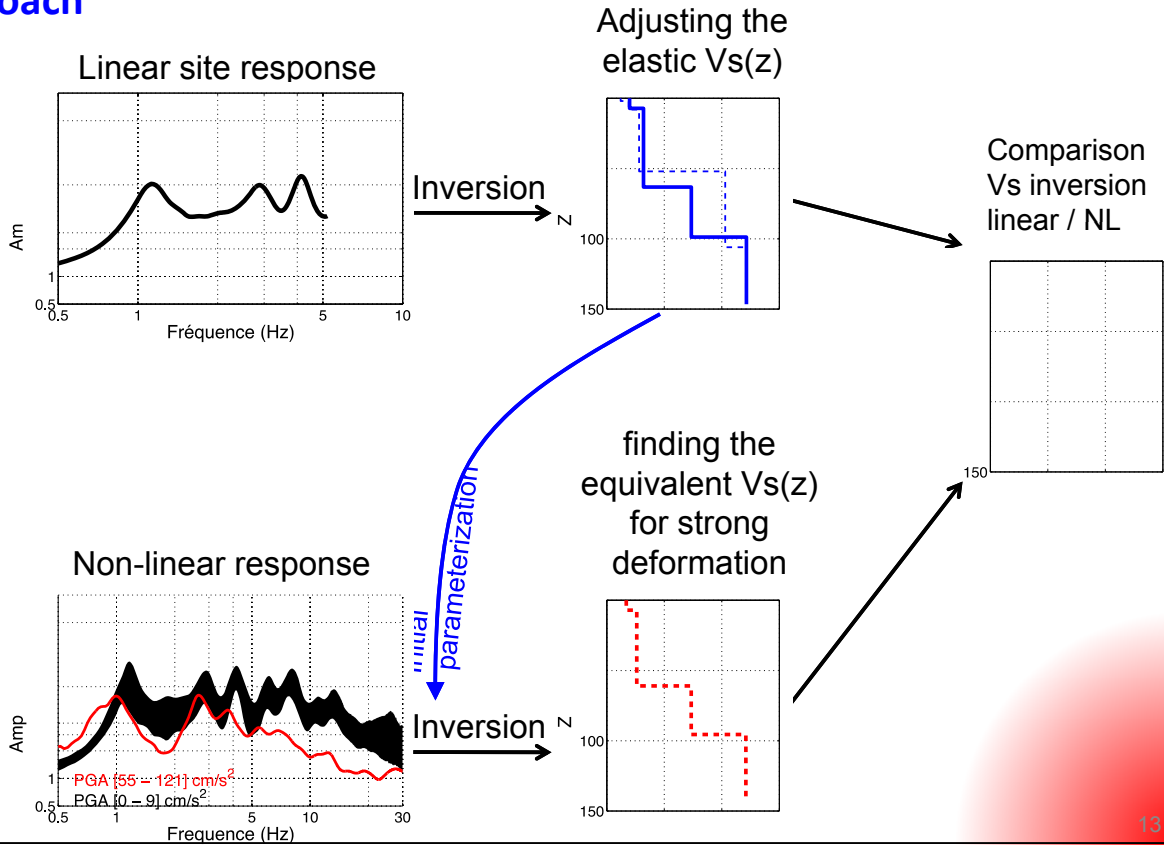
These observations suggest

- fNL between f_0 et f_{pred} : NL take mostly place in shallow soil layers?
- Measure of NL soil properties enough in the shallow soil layers to characterize the whole soil column NL response?
- Quantification of the depth where it occurs mostly?
- Use of inversion techniques: Inverting the site response to recover the equivalent V_s profile : Weak motion versus strong motion

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4- Inversion of linear/non-linear site response

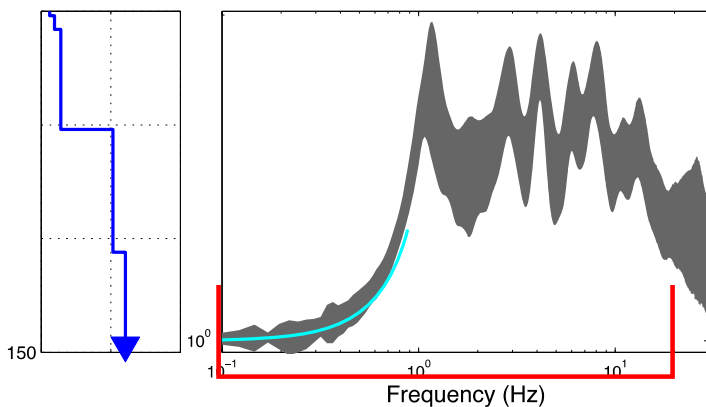
Approach



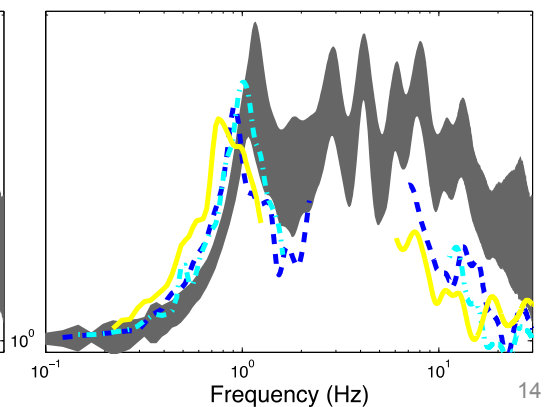
4- Inversion of linear/non-linear site response

Site selection criteria: - 1-D site configuration,
- with weak and strong motion recordings

Comparison empirical and numerical linear



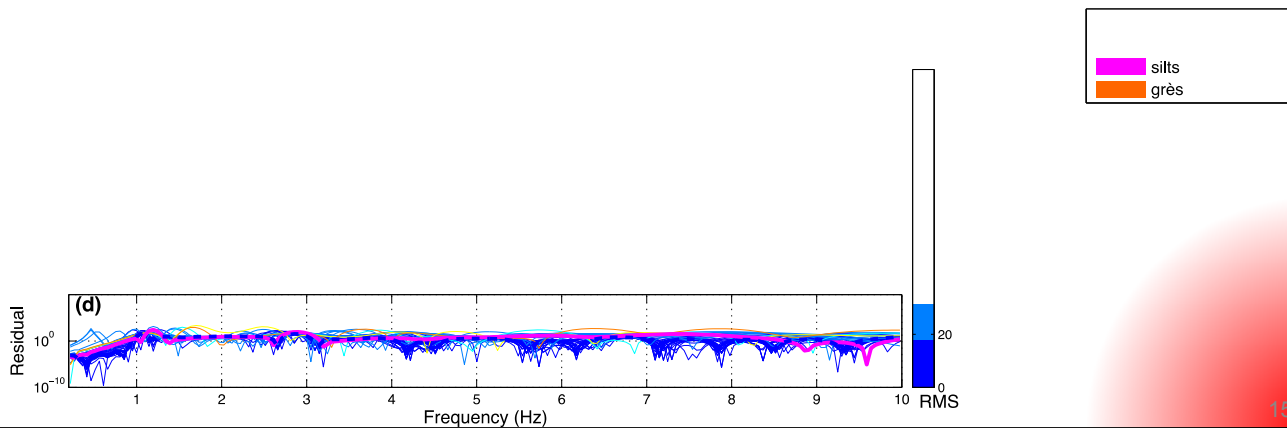
Comparison empirical linear and non-linear



4- Inversion of linear/non-linear site response

Vs ajustement

Best solution from inversion : layer 3 deeper
in agreement with geological log



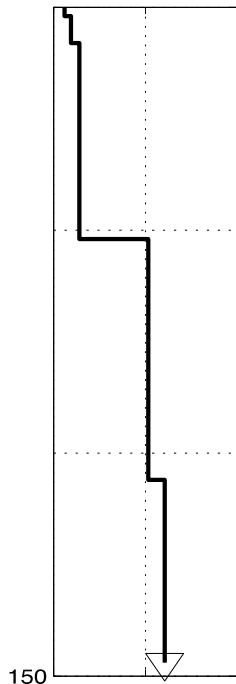
Inversion non-linear response

Parametrization & initial model

- Depth of soil layers fixed from linear inversion
- Vs intervals from linear inversion CV = 60 %
- Test on 3 EQs

EQ	M_{jma}	D_{epi}	Depth	PGA_{surf}
		Km	Km	cm/s^2
1	9	202	24	372
2	7.1	28	10	128
3	6.3	24	10	110

Inversion non-linear response



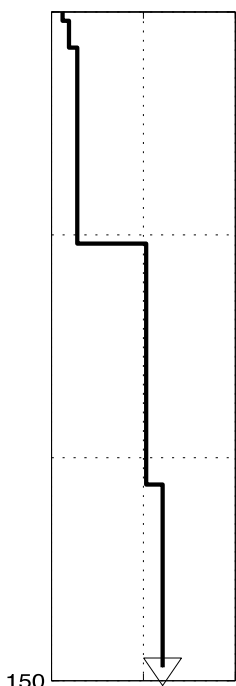
% of decrease of Vs compared to elastic properties

	EQ 1	EQ 2	EQ 3
PGA _{surf}	372	128	110
Vs1	150	43	16
Vs2	150	43	16
Vs3	31	13	20
Vs4	23	0.02	0.02
Vs5	-	-	-

- **EQs 2 et 3 : layers 1, 2 et 3 affected**
- EQ 1: layers 1, 2, 3 et 4 affected

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Inversion non-linear response



% of decrease of Vs compared to elastic properties

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- **EQs 2 et 3 : layers 1, 2 et 3 affected**
- EQ 1: layers 1, 2, 3 et 4 affected

Superficials layers more affected during the 3 Eqs
Deeper layers affected during the strongest

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Conclusions

Non-linear soil behaviour effects on site response:

- Decrease of amplification at high frequency
- **Amplification increase at low frequencies**

Probability of having large modification linear/non-linear site response is high even for moderate EQ ($PGA > 150 \text{ cm/s}^2$)

Site-specific analysis showed that NL soil behaviour:

- Occurs on superficial soil layers
- Depth also depends on incident motion intensity

In accordance with previous studies:

- *Regnier et al 2013: Statistical analysis on 54 KiK-net sites*
- *Aguirre and Irikura (1997): Vs reduction in the second layer between 5 m to 16 m depth*
- *Pavlenko and Irikura (2006) Soil nonlinearity in the upper 15-25 m of the soil profiles*
- *De Martin et al. (2010) Vs reduction occurred mostly around 35 m depth*
- *Assimaki and Li (2012), showed that Vs30 (superficial soil parameter) was a relevant parameter to analyze non-linear site responses*

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Thanks for your attention!!!

Bonilla, L. F., Tsuda, K., Pulido, N., Regnier, J., & Laurendeau, A. (2011). Nonlinear site response evidence of K-net and KiK-net records from the Mw 9 Tohoku earthquake. *Earth Planets Space*, 58.

Régnier, J., Cadet, H., Bonilla, F.-L., Bertrand, E., Semblat, J.-F. (2013-a) Assessing nonlinear behavior of soils in seismic site response: Statistical analysis on KiK-net strong motion data. *Bulletin of Seismological Society of America*, accepted in february 2013, Volume 103, Issue 3.

Régnier, J., Bonilla, F.-L., Bertrand, E., Semblat, J.-F. Influence of the velocity profile at depth on the linear characterization of site effects: Tests on the KiK-net database, *Bulletin of Seismological Society of America*, submitted in january 2013-b

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