Simulating site-specific nonlinear site response in low-to-moderate seismicity areas – insight from Switzerland

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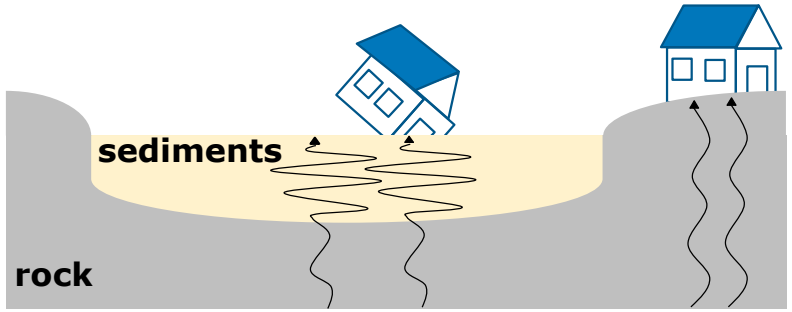
Sharing is encouraged

Introduction

Linear site response

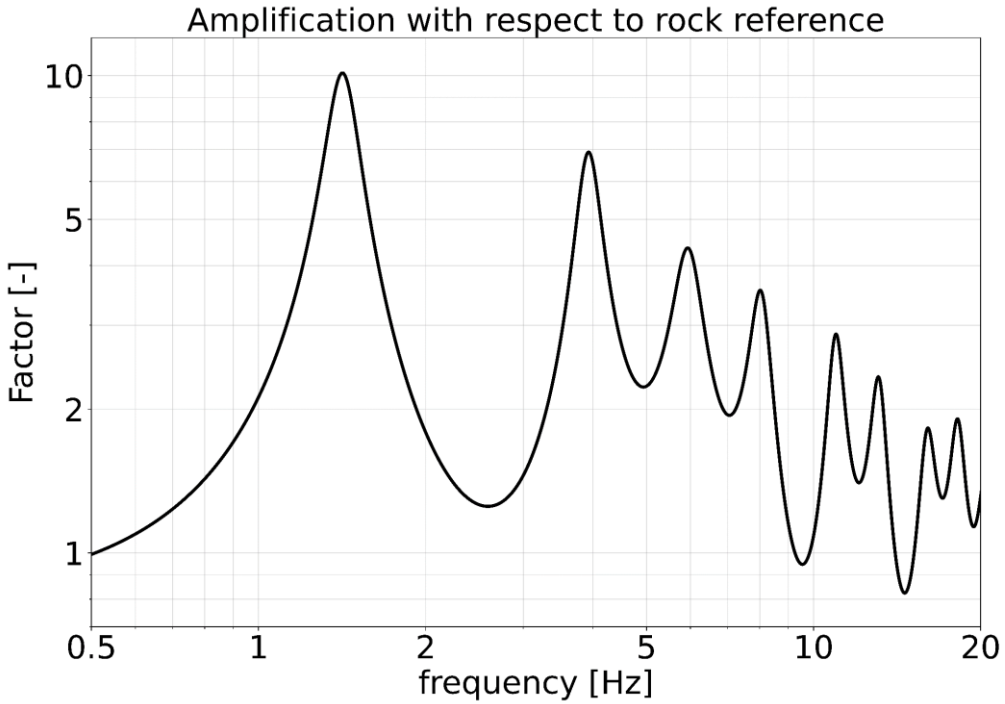
Soil parameters – **constant**

Earthquake strength



Modified after Ciaccio and Cultrera (2014)

Independent on the ground motion



Soft sedimentary basins

Ground motion amplification

Increase damage

Importance of nonlinearity

Linear site response

Soil parameters – **constant**

Nonlinear site response

Soil parameters – **strain dependant**

Earthquake strength

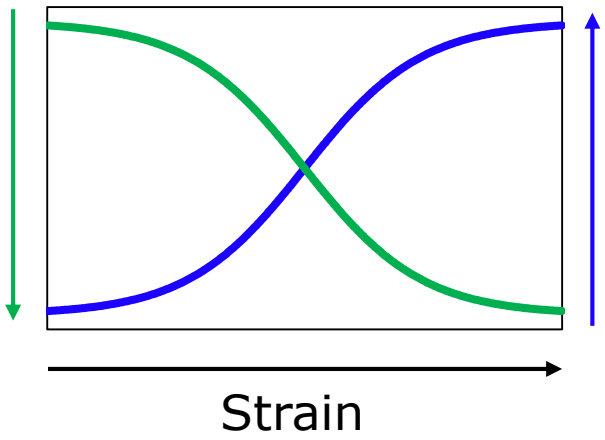
- Change to amplification factors
- Change to resonance pattern

Shear modulus

+

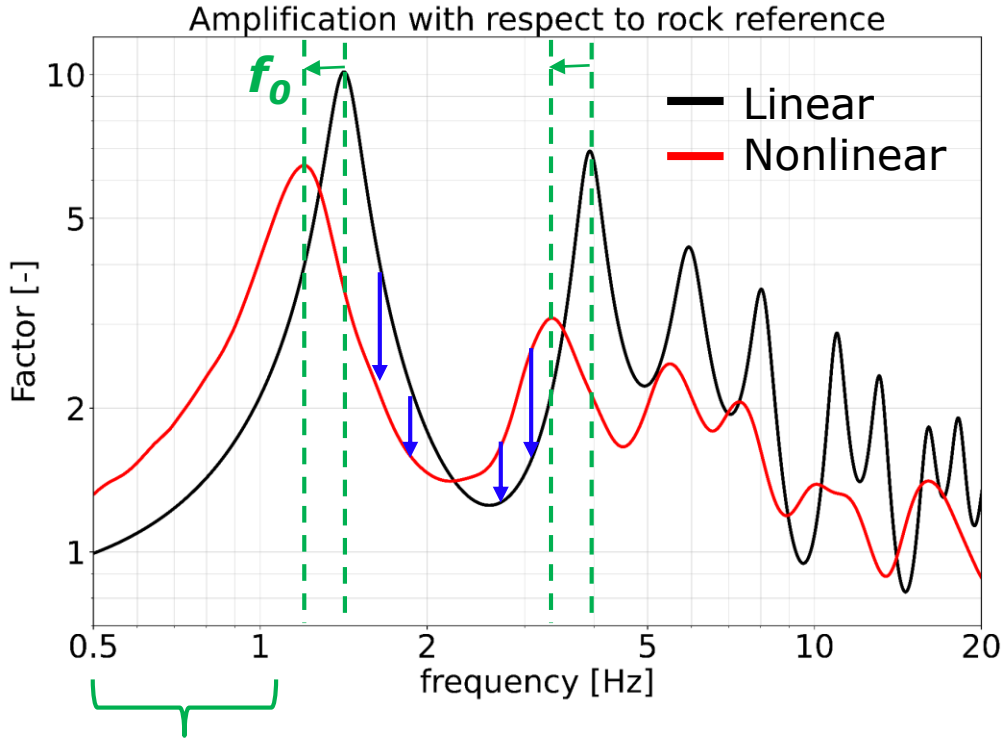
Shear wave velocity (V_s)

Fundamental frequency (f_0)



Damping

Dependent on the ground motion



Increase of amplification

Importance of nonlinearity

Linear site response

Soil parameters – **constant**

Nonlinear site response

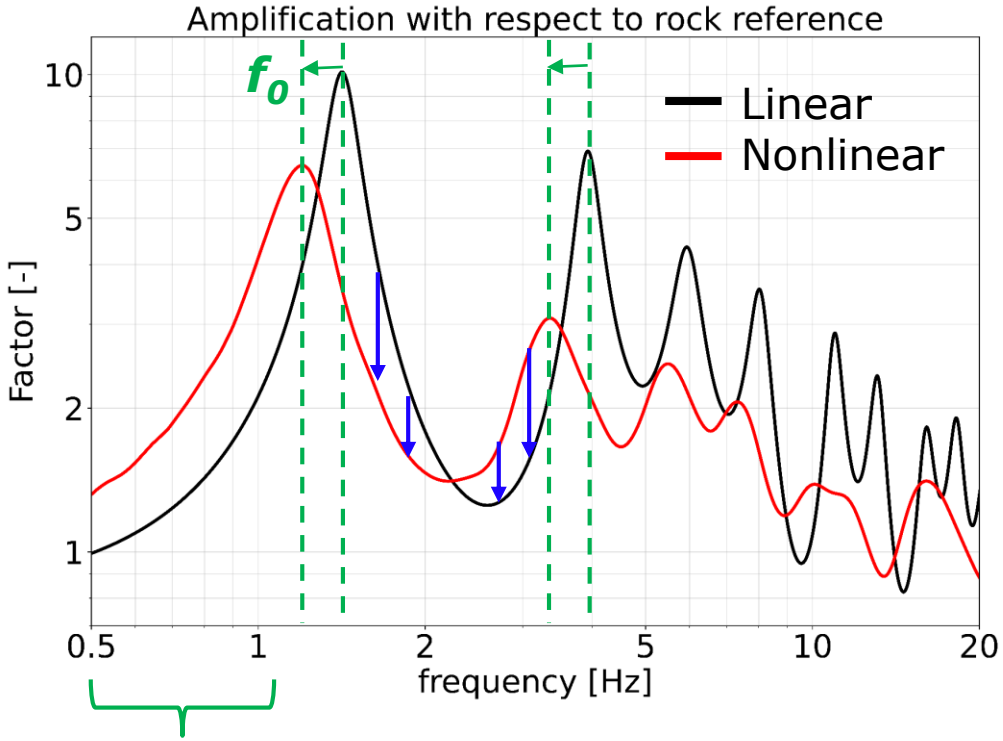
Soil parameters – **strain dependant**

Earthquake strength

- Change to amplification factors
- Change to resonance pattern

+ secondary phenomena: **liquefaction**

Dependent on the ground motion



How to estimate nonlinearity?

~~**Observations**~~ ⟷ **Numerical simulations**

- Complexity

Fully nonlinear ⟷ Linear equivalent

- Complex behaviour
- Many parameters
- Computational demanding

- Not many parameters
- Well-known, relatively fast
- Simplified

+ **Pore pressure excess** development

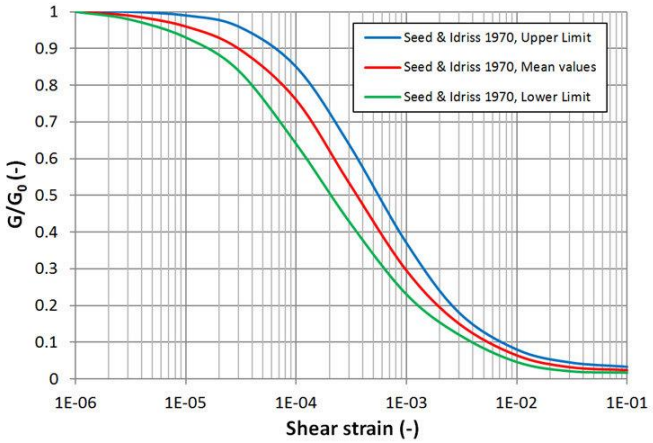
+ **Liquefaction**

How to estimate nonlinearity?

~~Observations~~ ⟷ **Numerical simulations**

- Soil models

Literature ⟷ ~~Strong motion~~



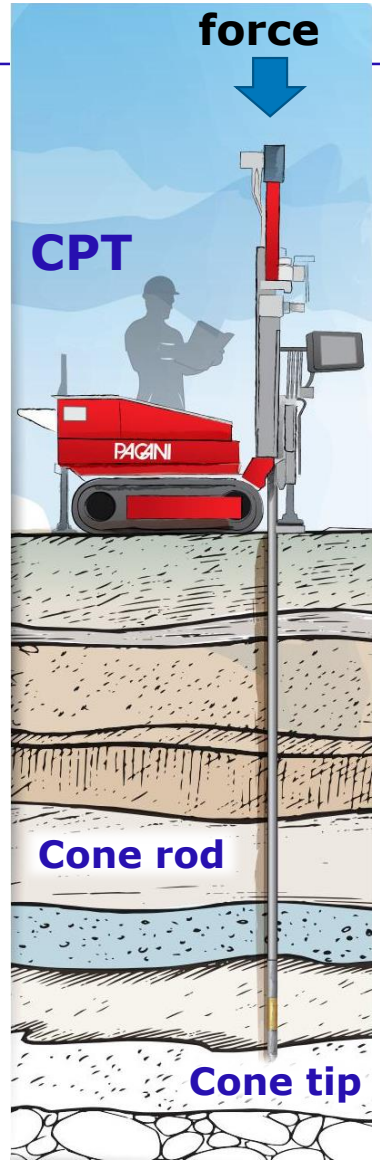
Seed and Idriss (1970)

Laboratory

- Direct measurements
- Expensive
- Sampling problems
- Ex-situ

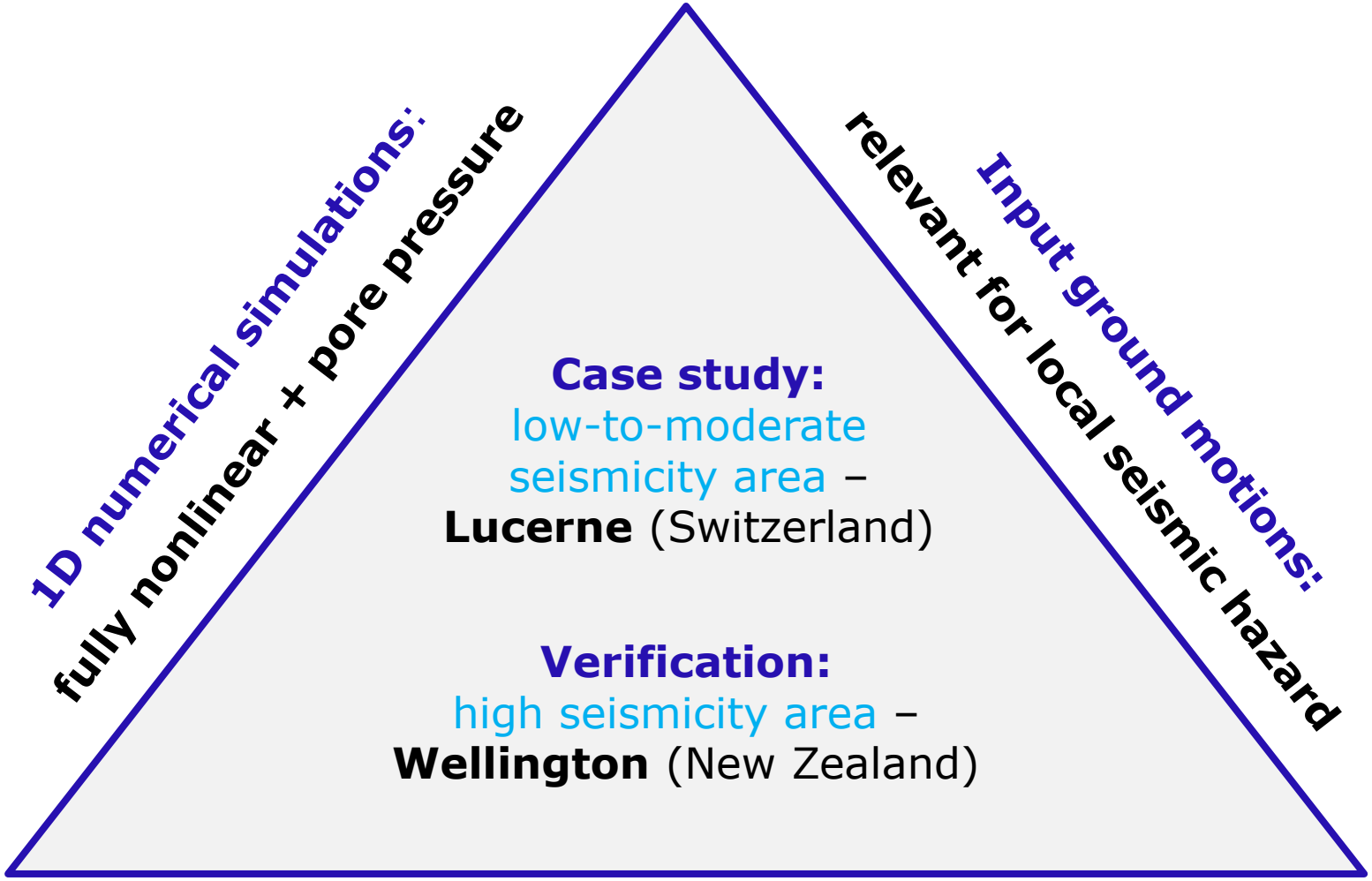
Cone Penetration Test (**CPT**)

- In-situ
- Availability
- Empirical relations



Lo Presti & Meisina (2019)

Idea and goal



Site-specific soil models: CPT

Methodology

Workflow

Soil model definition (**CPT** + other data)

↓

Inversion for dilatancy parameters (Roten, 2014) from **CPT**

↓

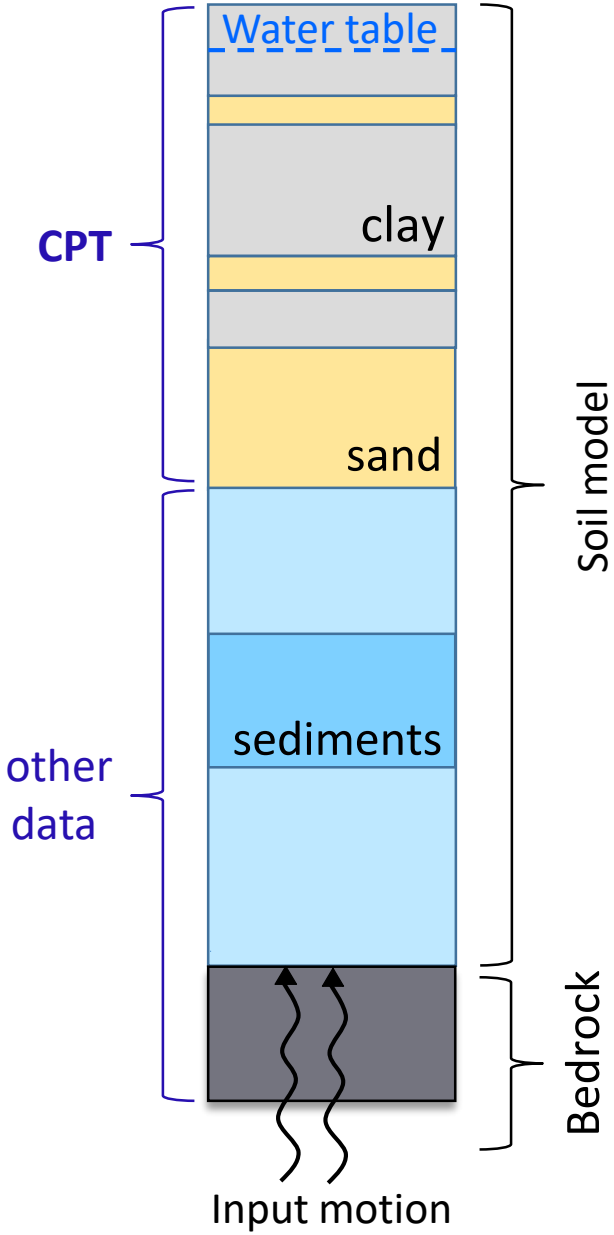
Input ground motions relevant for the area

↓

1D simulations of wave propagation (Bonilla et al., 2005)

↓

Acceleration, strain, pore pressure



Janusz et al. (2024), GJI
Janusz (2024), Doctoral Thesis

Case study area:
low-to-moderate seismicity area –

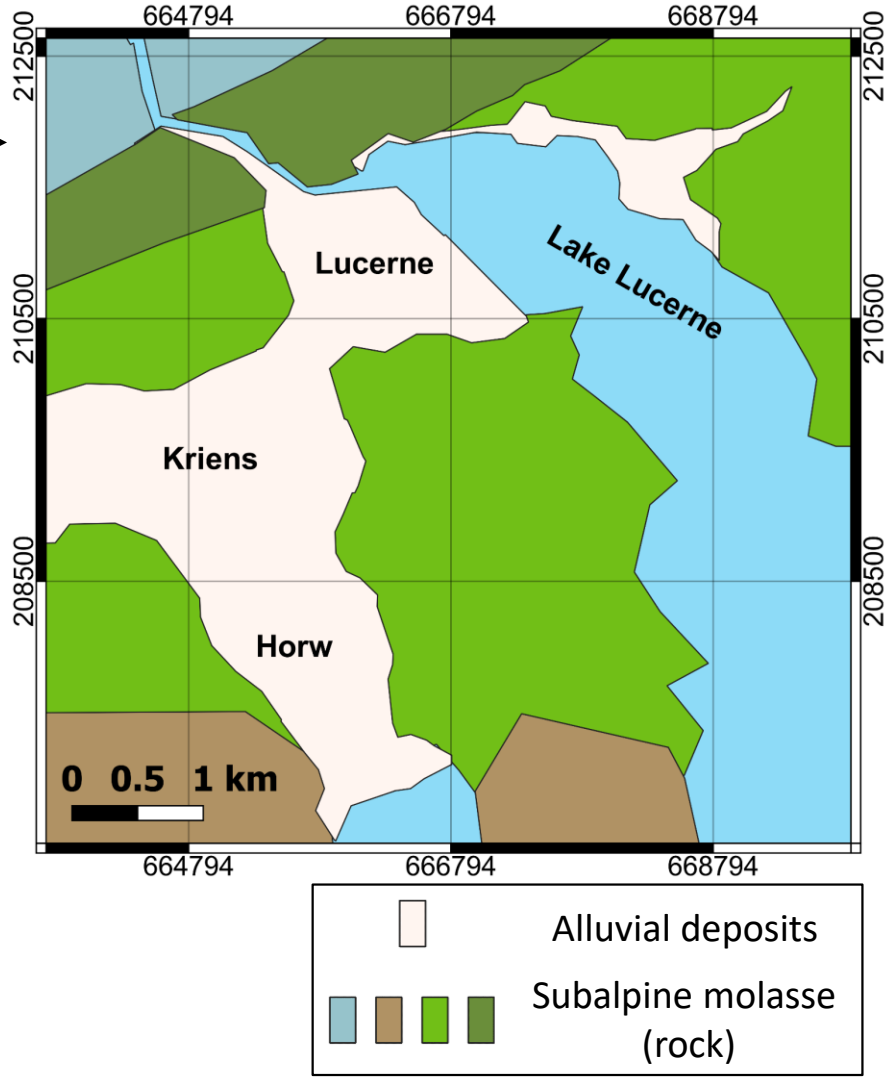
Lucerne (Switzerland)

Geology and seismic hazard

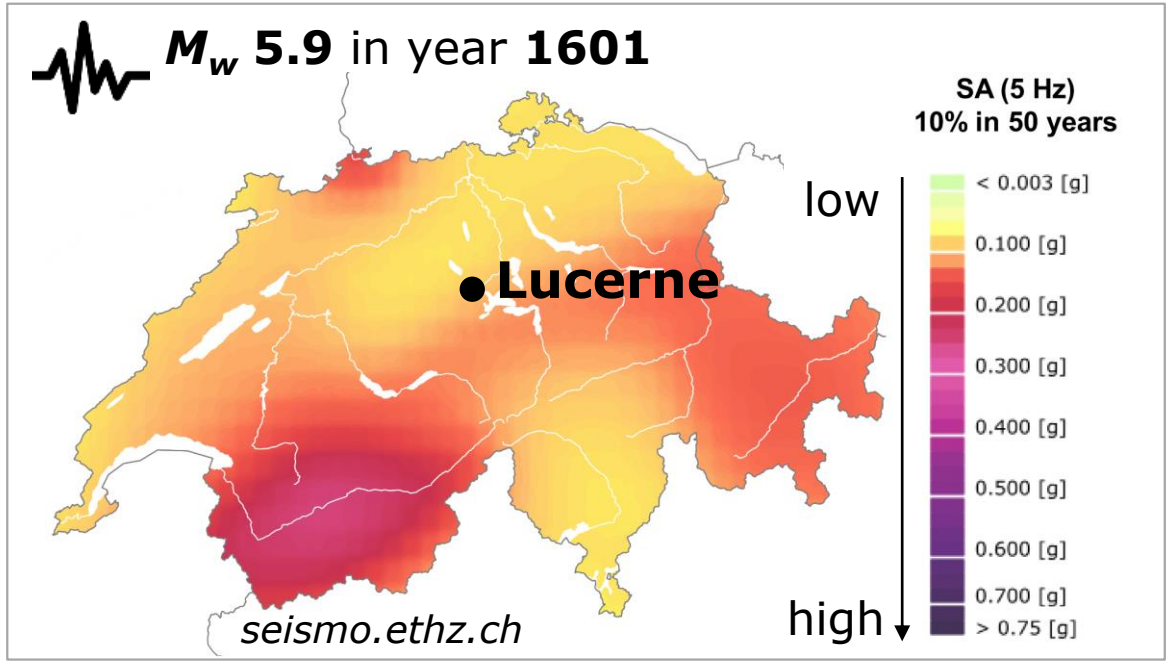
Soft sedimentary basin:

Very **soft alluvial** deposits (V_{S30} < 300m/s)

Shallow water table (~1-4 m)



SEISMIC HAZARD MAP



Low-to-moderate seismicity area with some strong **historical earthquakes**

Geology and seismic hazard

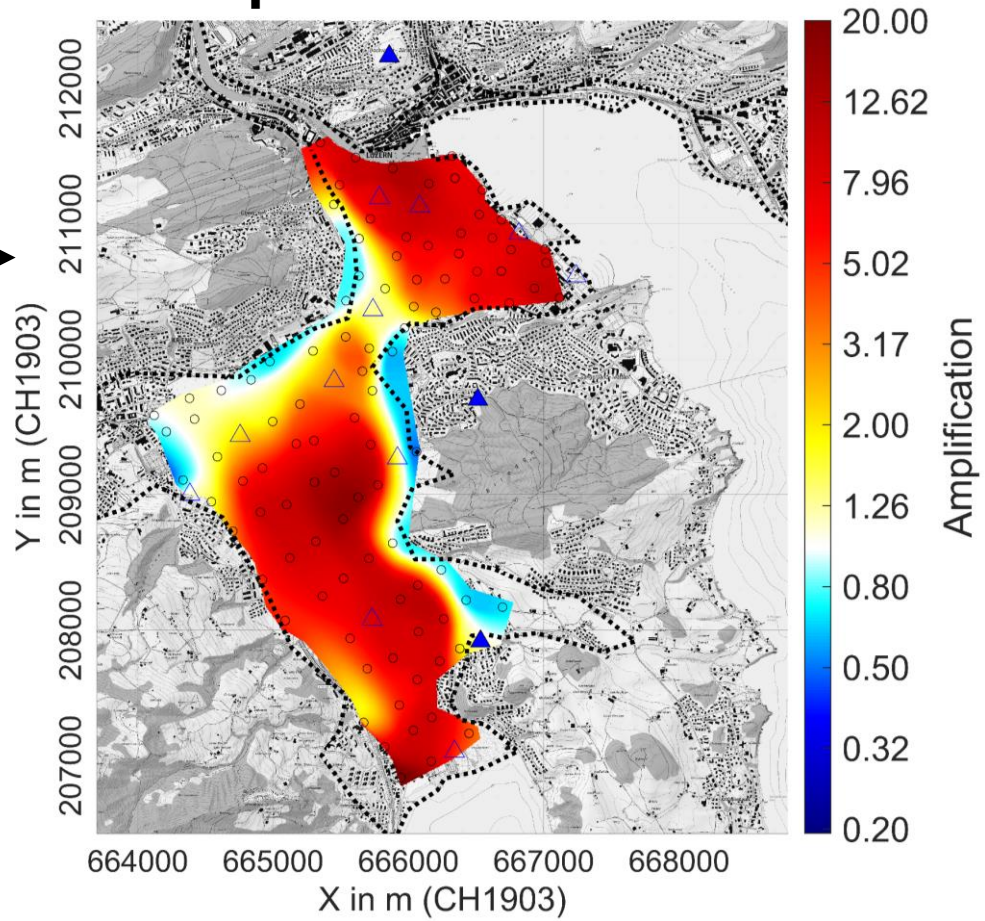
Soft sedimentary basin:

Very **soft alluvial** deposits (V_{S30} < 300m/s)

High **amplification** (>10) in linear domain

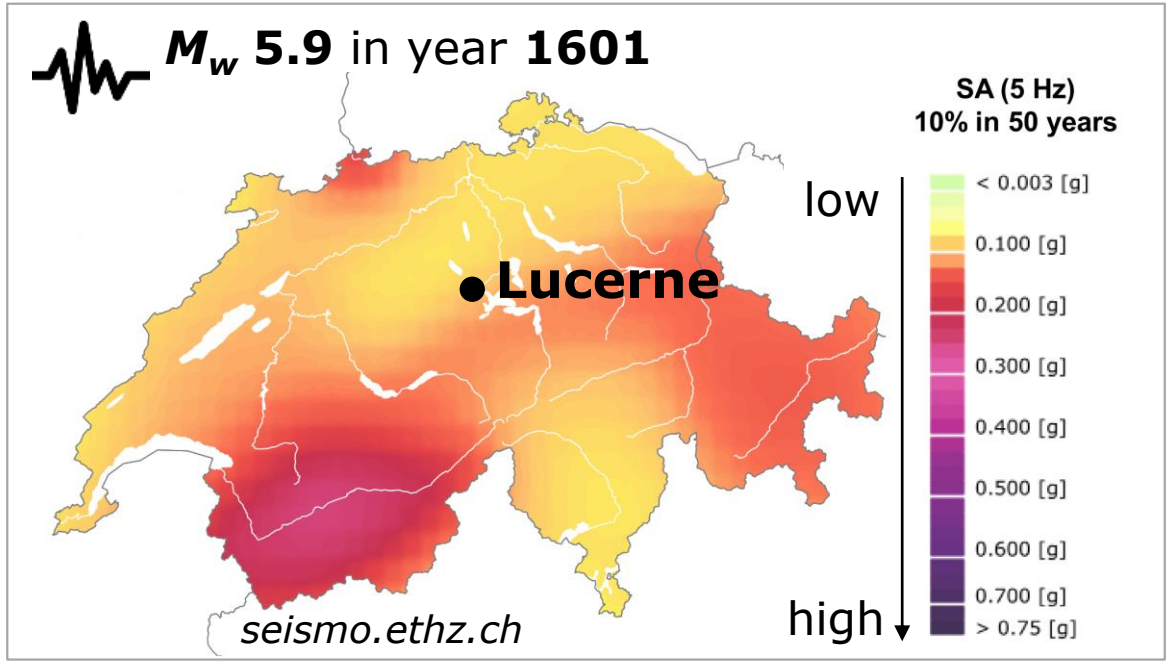
Shallow water table (~1-4 m)

Amplification at 1.7 Hz



Janusz et al. (2022)

SEISMIC HAZARD MAP



Low-to-moderate seismicity area with some strong **historical earthquakes**

Data

Sites:

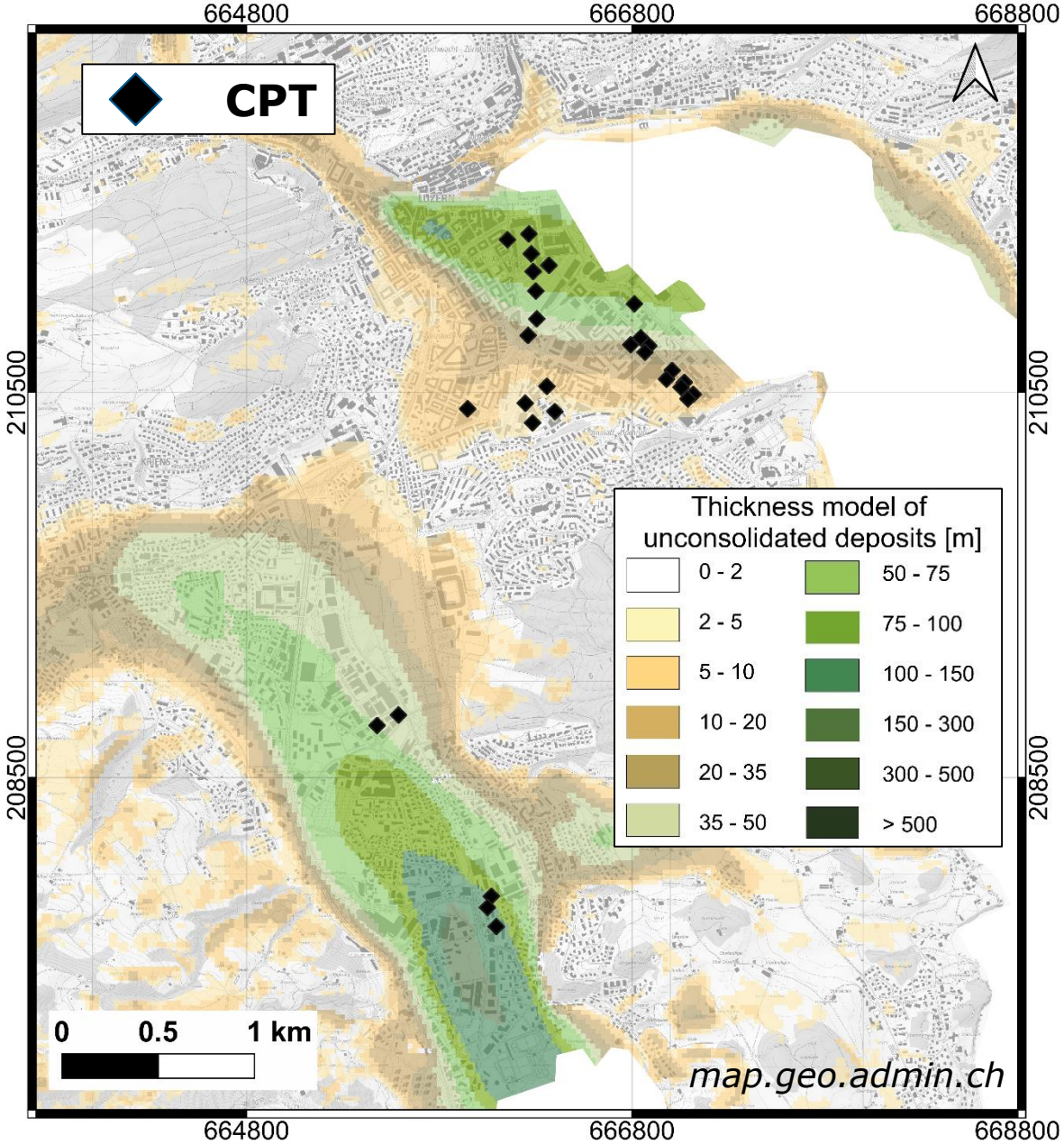
29 CPT locations ◆

Soil models:

CPT
+
***V_s* model** (Poggi et al. 2012)
Geological data (map.geo.admin.ch)
Borehole data

Input motions:

database of waveforms consistent with **local seismic hazard** for **475** and **975** years return periods (Panzera et al., 2024)



Results: Lucerne

Janusz et al. (2024), GJI
Janusz (2024), Doctoral Thesis

Impact of nonlinearity (single site)

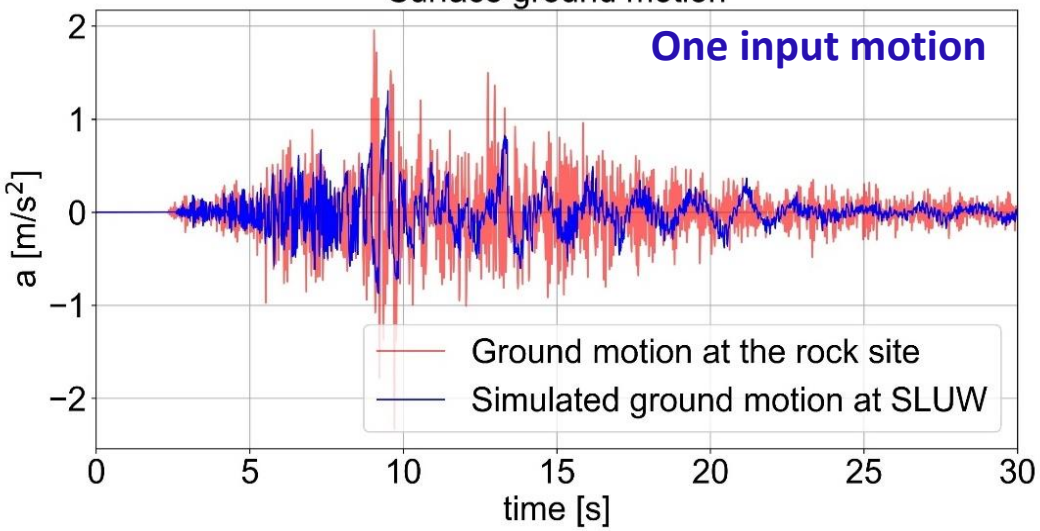
(1 site, input motions for 975 yr return period)

Diminished amplitude

Reduced high-frequency content

↓

Surface ground motion

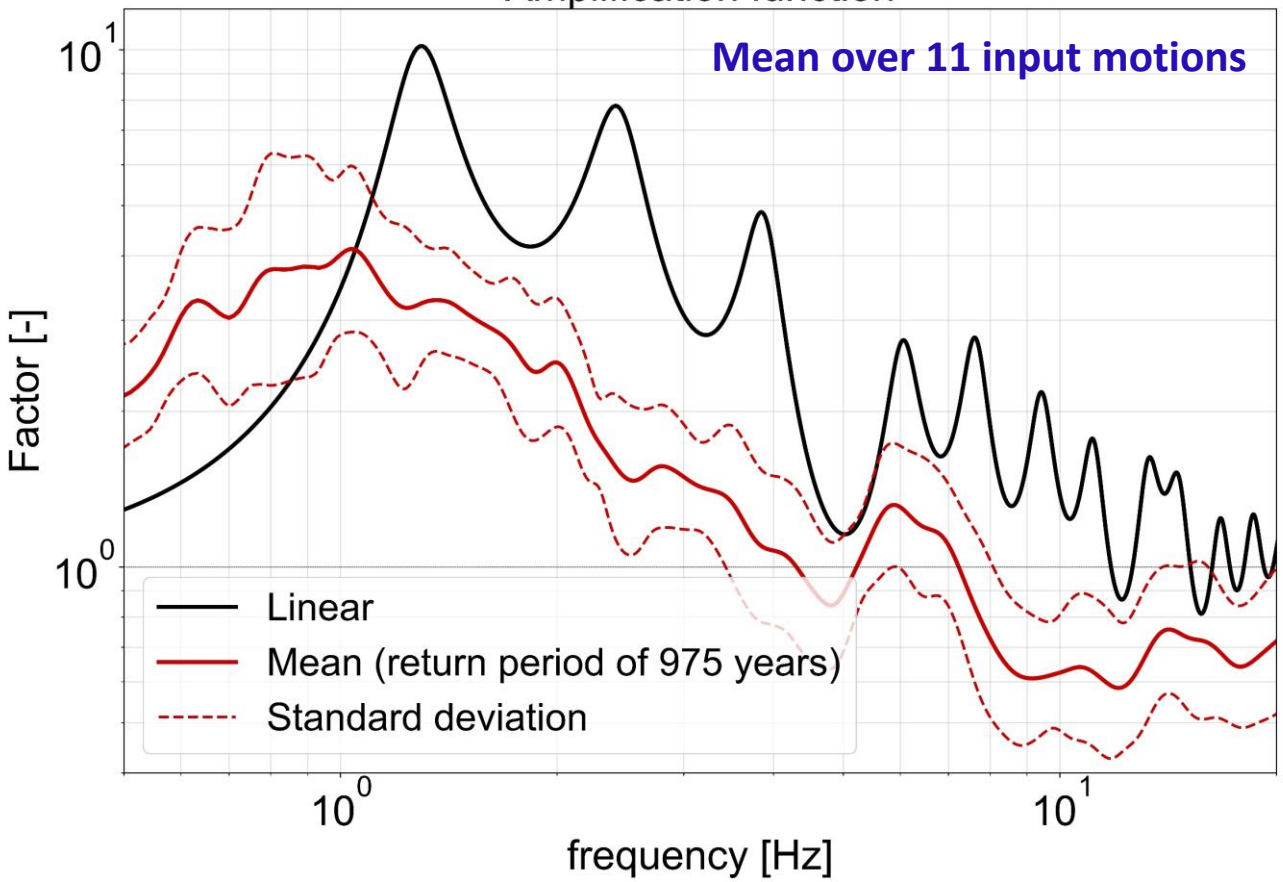


Reduced amplification / deamplification

Shift of amplification peaks + increase of amplification

↓

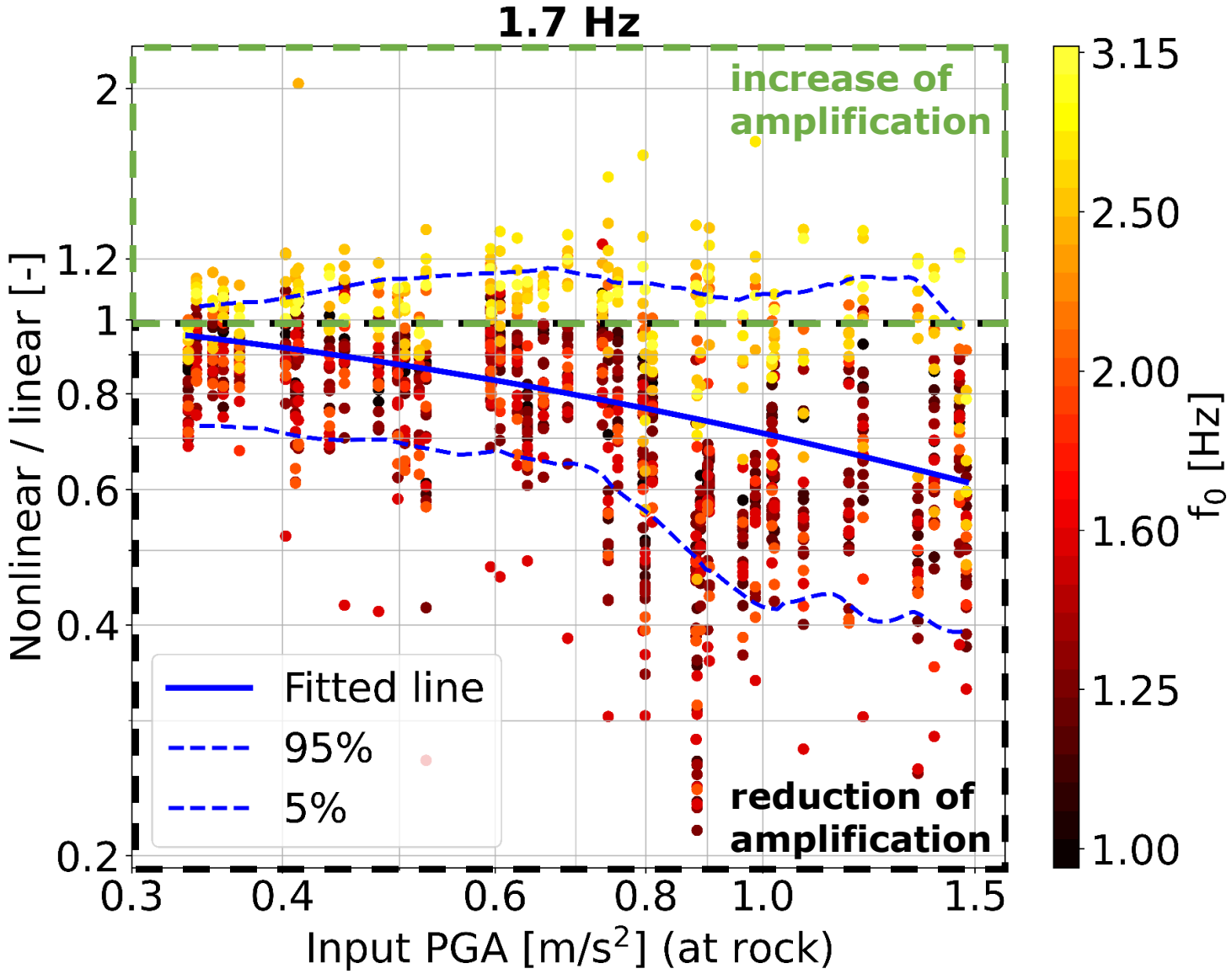
Amplification function



Variability

29 sites
44 input motions –
different hazard levels

***PGA** = **P**eak **G**round **A**cceleration*



Some **correlations** with:

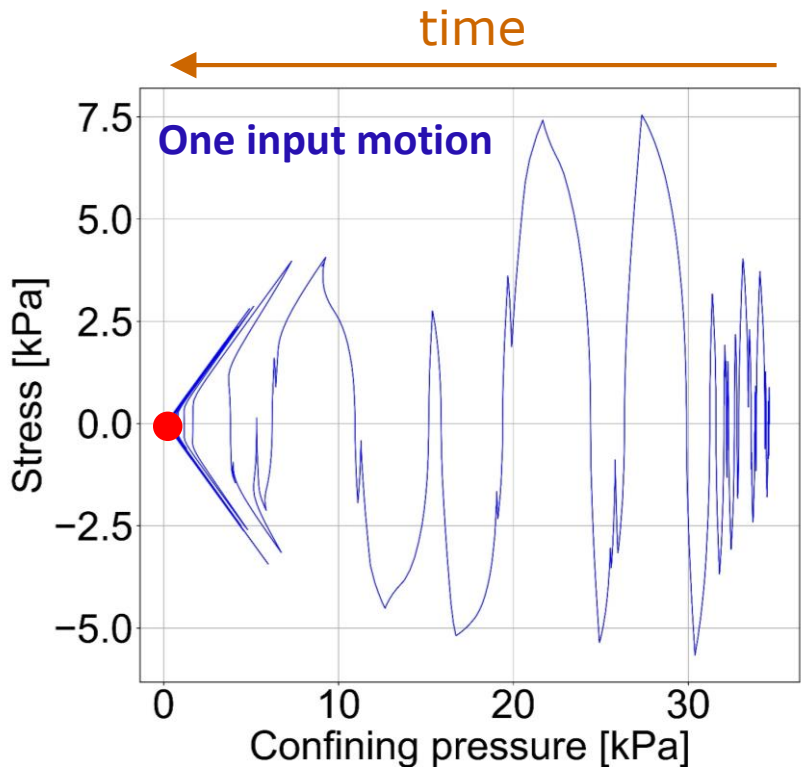
- ***f_0***
- water table depth
- bedrock depth
- soil classes

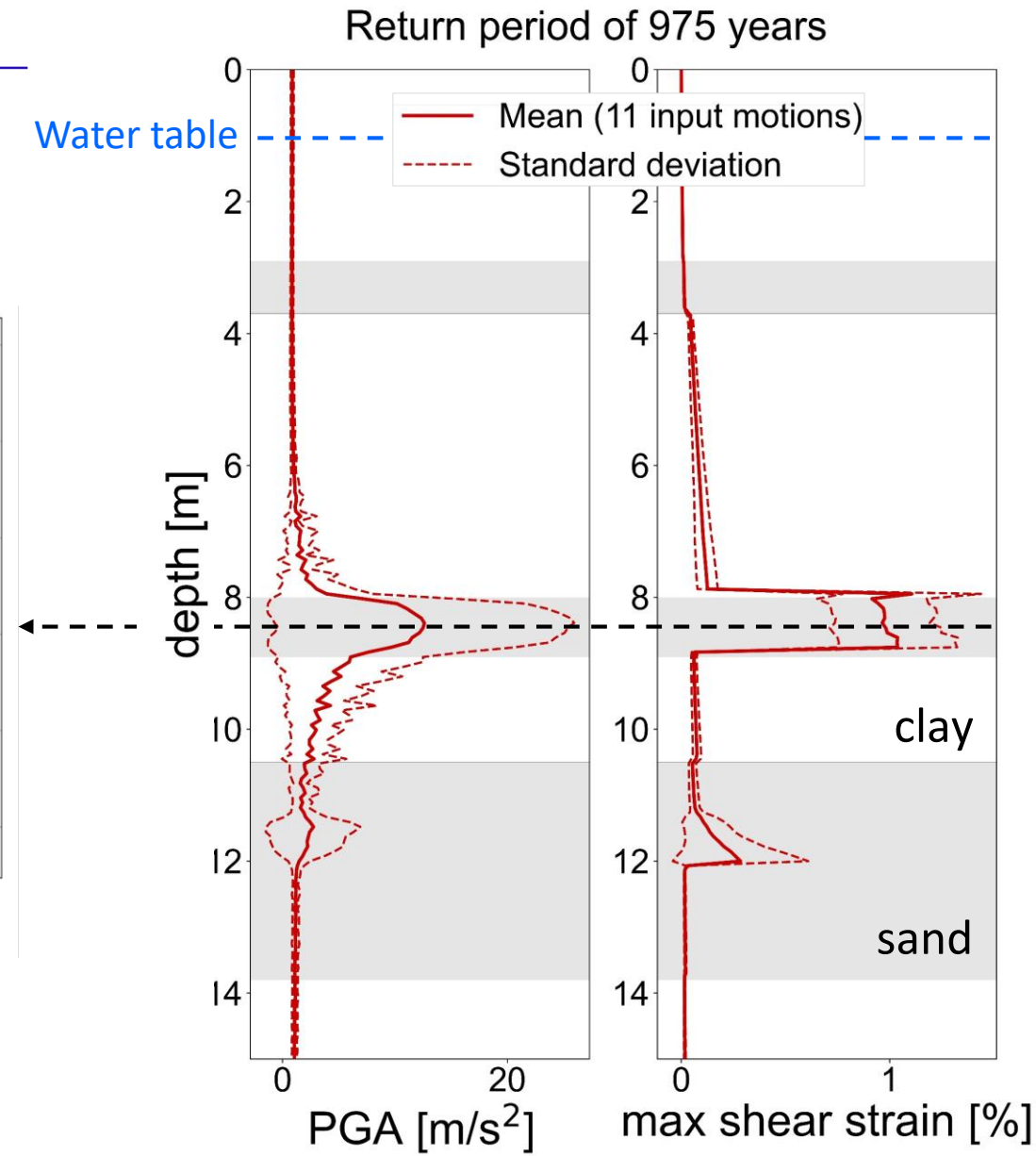
Nonlinearity and **variability** of behaviour

Liquefaction potential (single site)

(1 site, input motions for 975 yr return period)

***PGA** = **P**eak **G**round **A**cceleration*





LIQUEFACTION

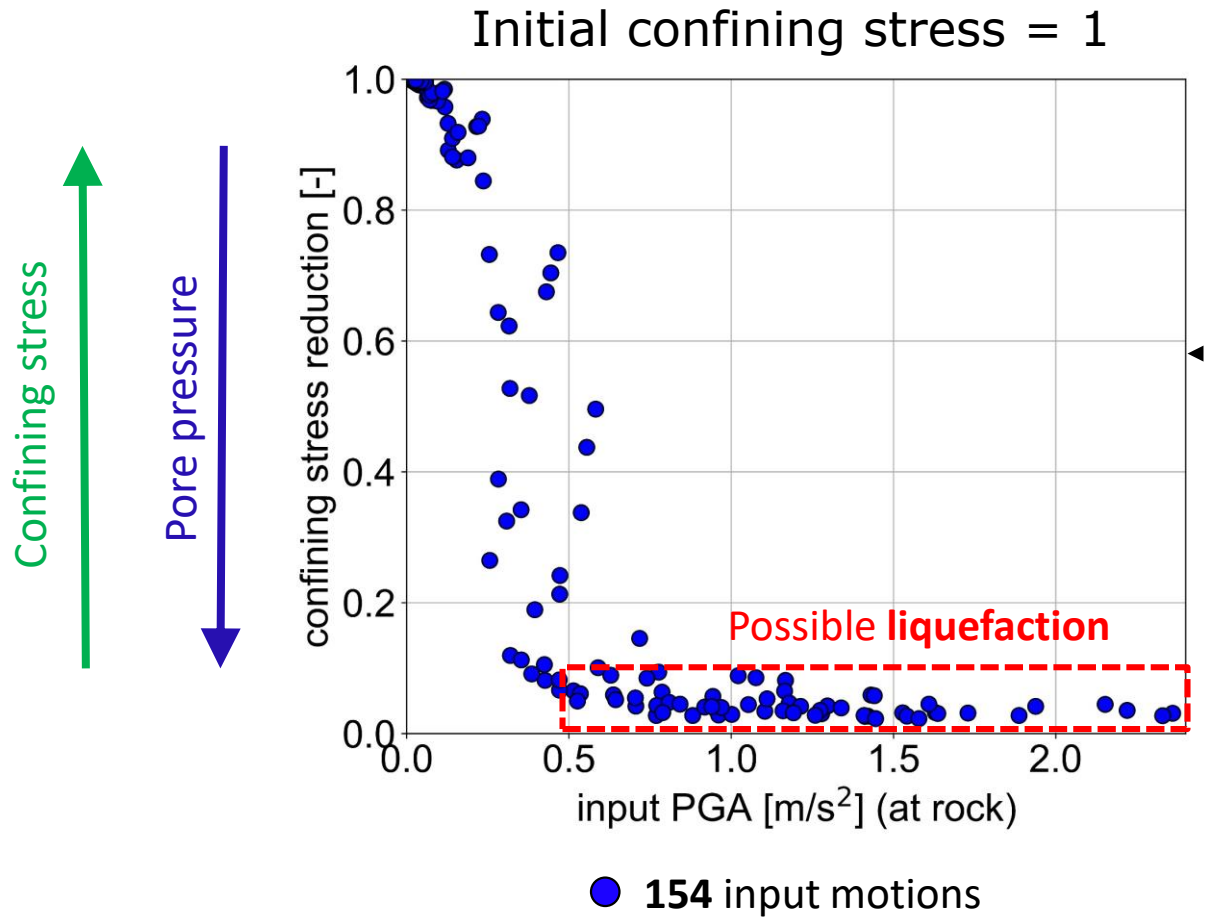
↑

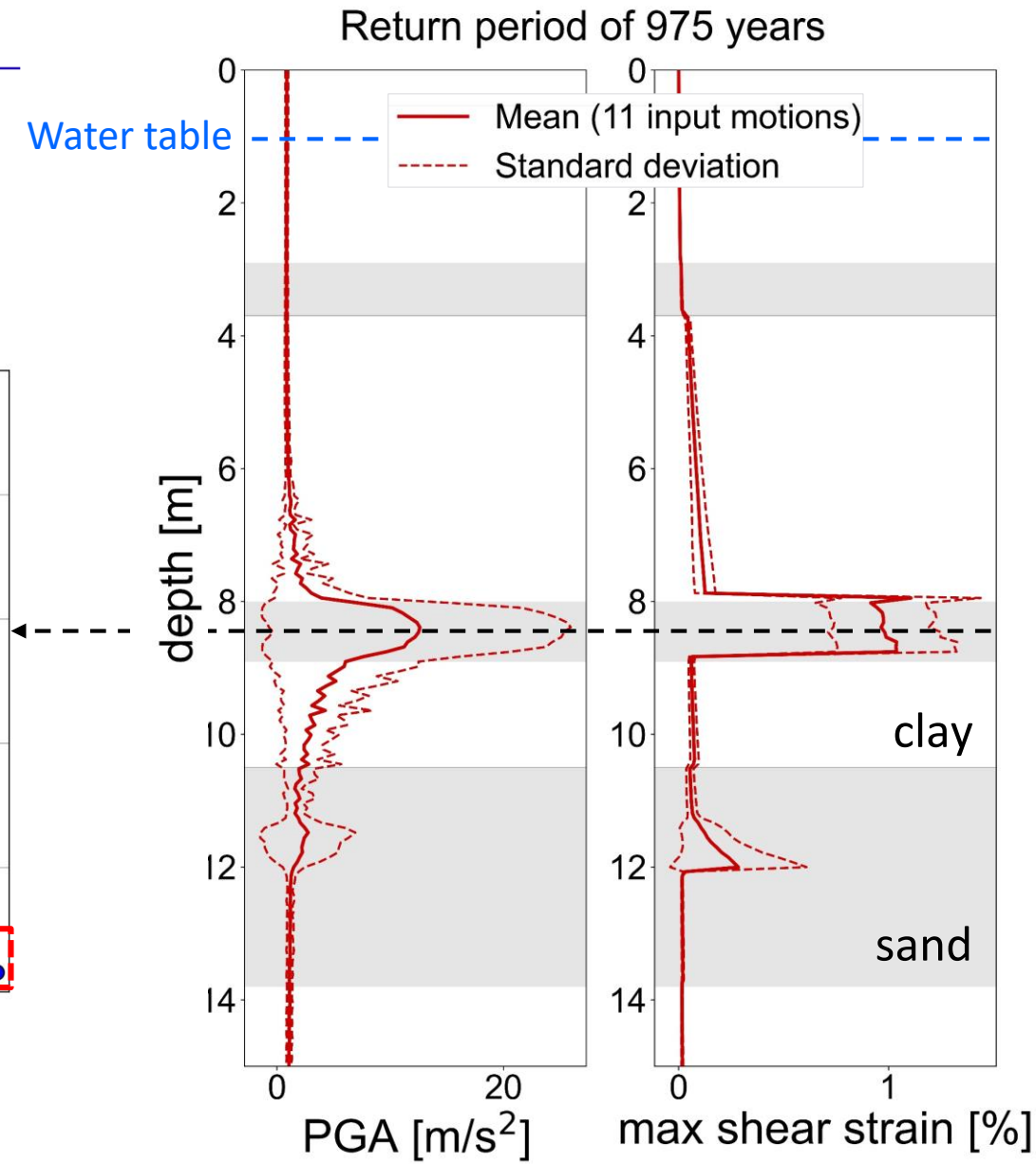
No shear strength ← **Reduction of the confining stress** ↓ **Pore pressure build-up**

Liquefaction potential (single site)

(1 site, input motions for 975 yr return period)

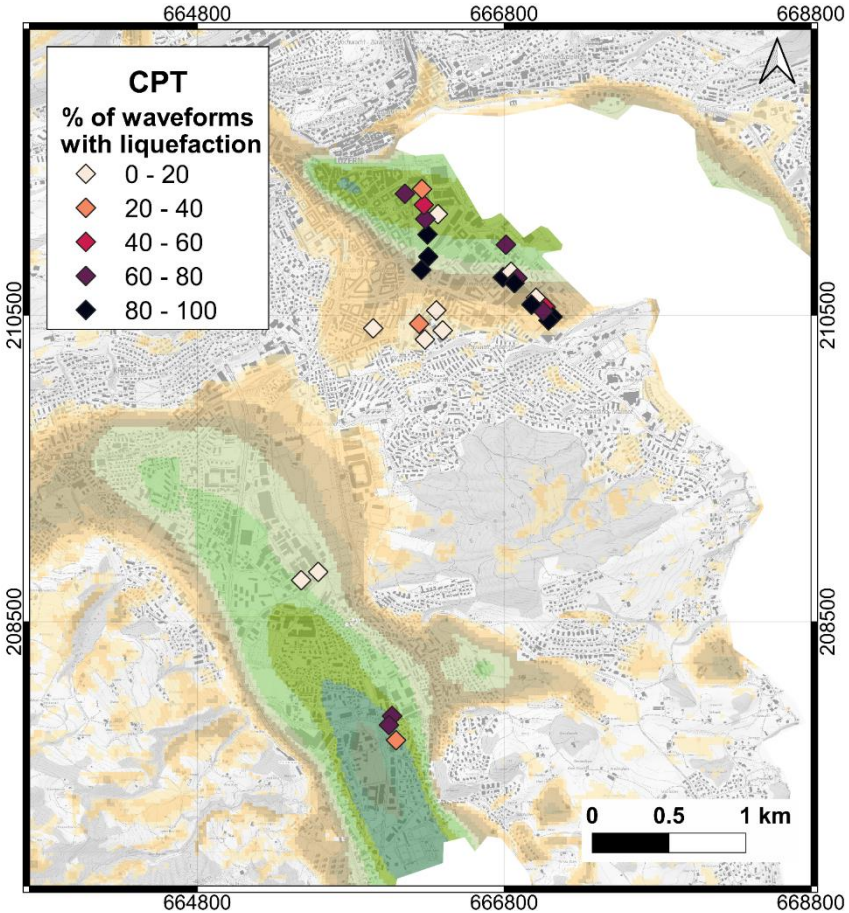
***PGA** = **P**eak **G**round **A**cceleration*





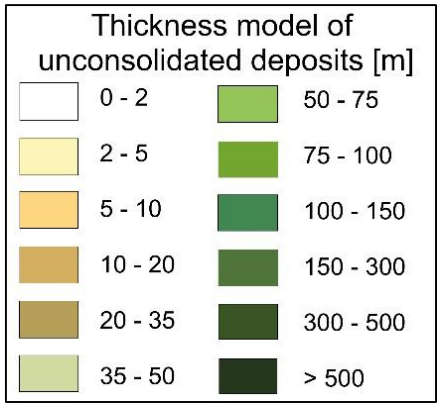
Liquefaction onset in at least one layer

475 years return period

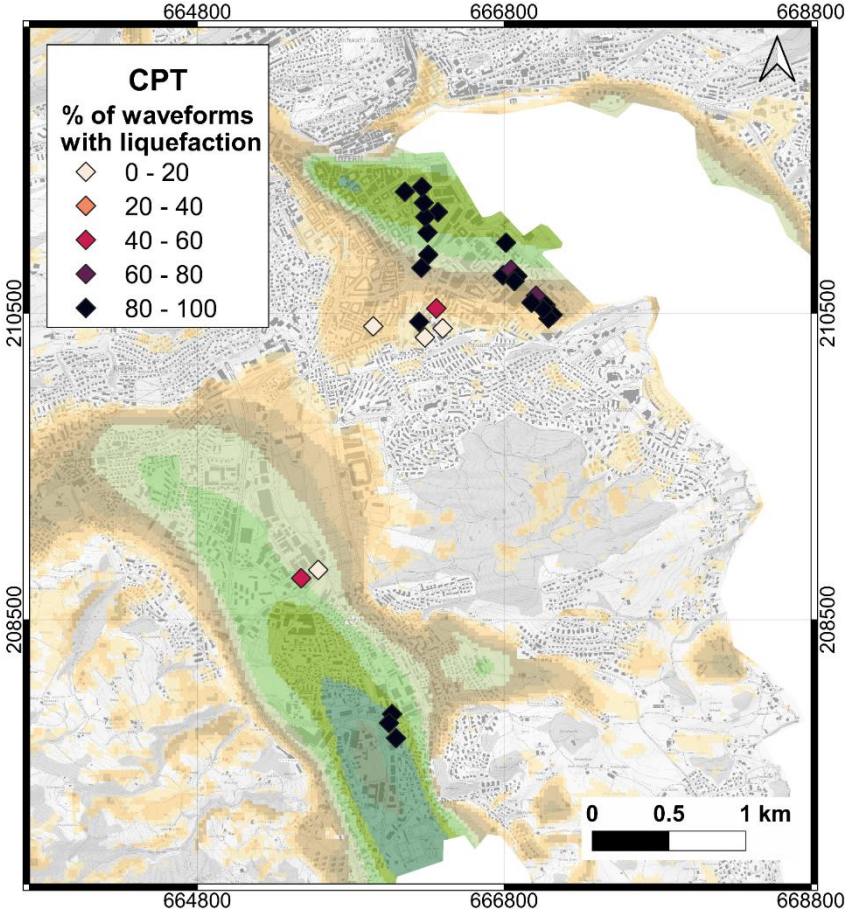


29 sites, 11 input motions

Criterion:
90% reduction of initial confining stress



975 years return period



Verification:
high seismicity area –

Wellington (New Zealand)

Location and motivation

britannica.com

wikimedia.org

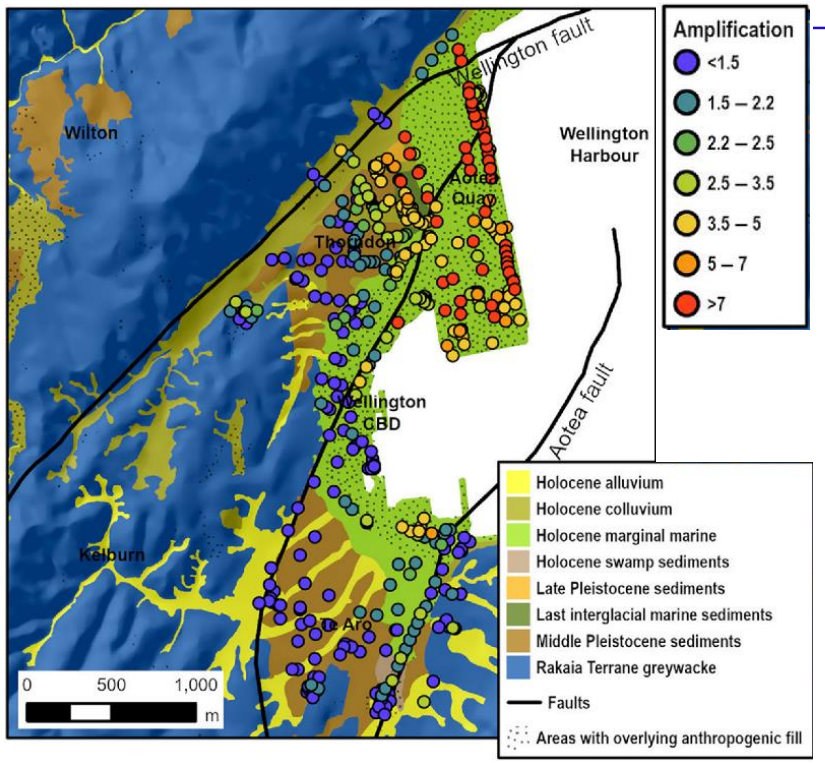
- Soft sedimentary basin
- Liquefaction susceptibility
- High amplification factors

Wellington area

2013 Cook Strait earthquake (M_w **6.6**)
2013 Grassmere earthquake (M_w **6.6**)
2016 Kaikōura earthquake (M_w **7.8**)

Nonlinearity and **liquefaction** observed in **Wellington**
e.g. Hancox et al. (2013), Cubrinovski et al. (2018), Zhou et al. (2020)

Amplification at 1 Hz



Manea et al (2023a)

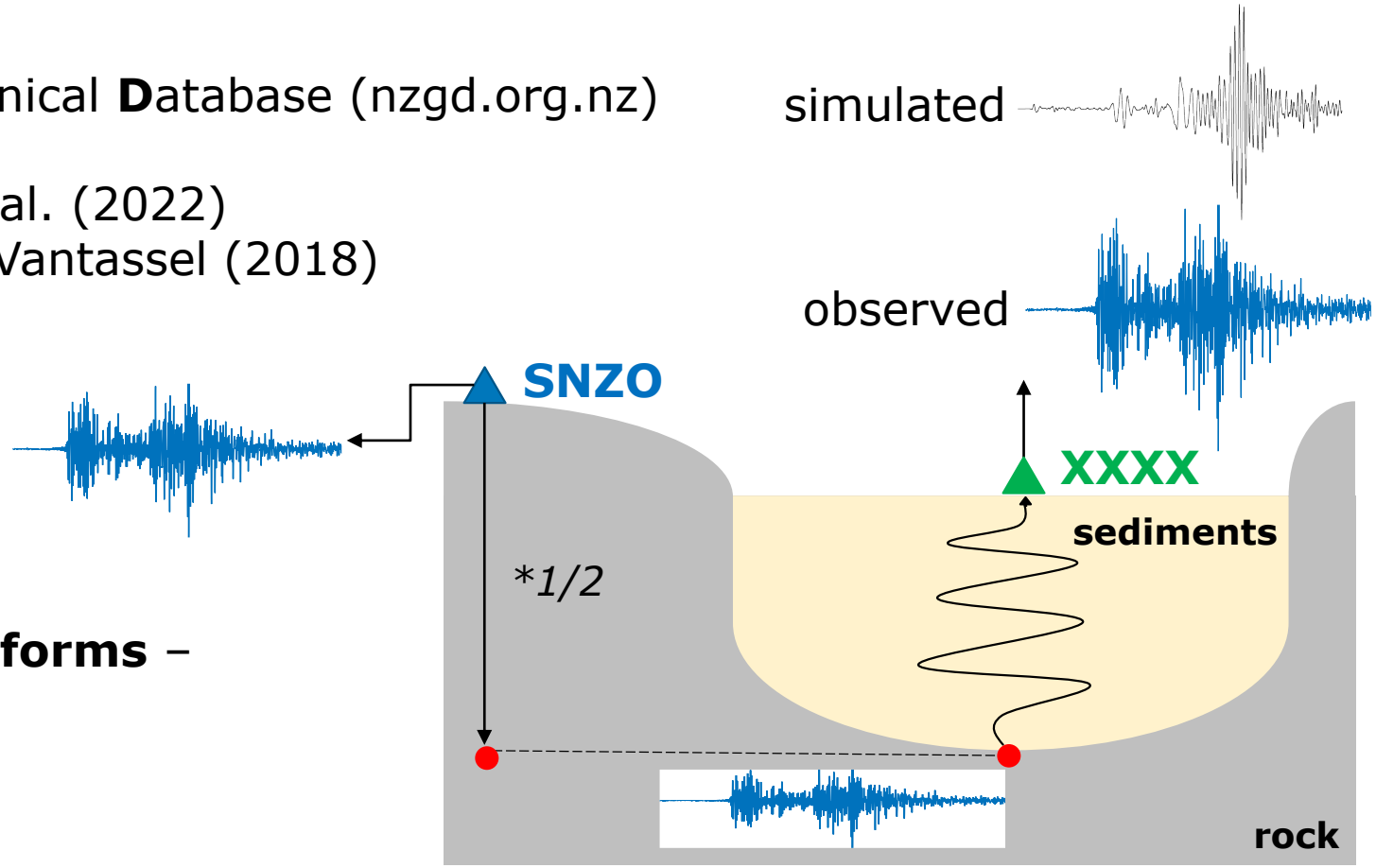
Data and idea

Sites:

GeoNet seismic stations (geonet.org.nz) in **CentrePort, Wellington**

Soil models:

CPT – **N**ew **Z**ealand **G**eotechnical **D**atabase (nzgd.org.nz)
+
3D velocity model – Hill et al. (2022)
***V_s* measurements** – Cox & Vantassel (2018)



Input motions:

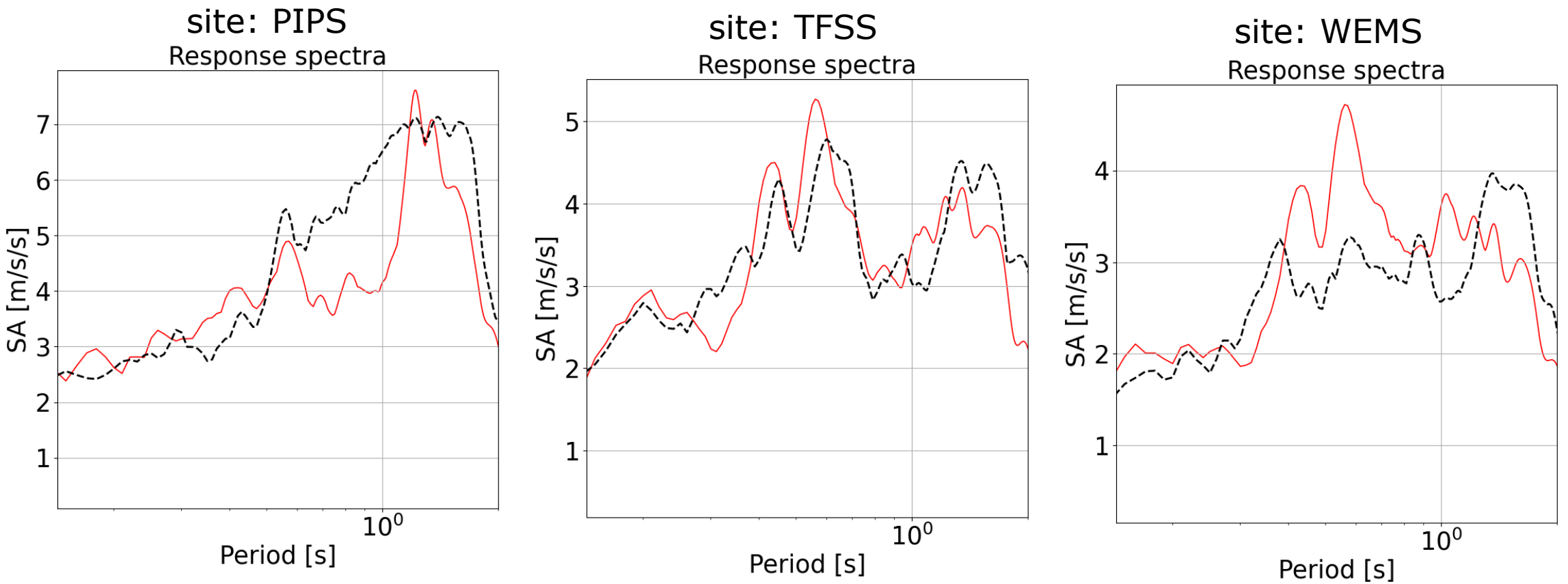
Database of **recorded waveforms** – Manea et al. (2023b)

Results: Wellington

ongoing work...

Examples of the results

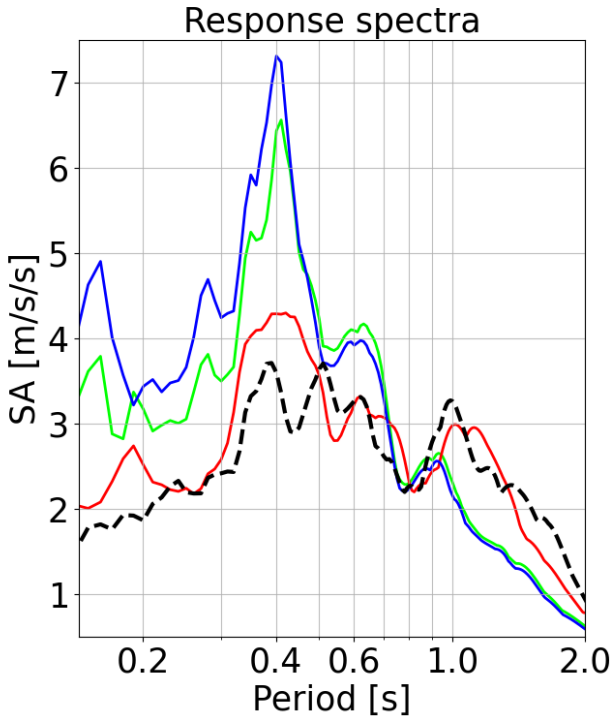
2016 Kaikōura earthquake (M_w **7.8**)

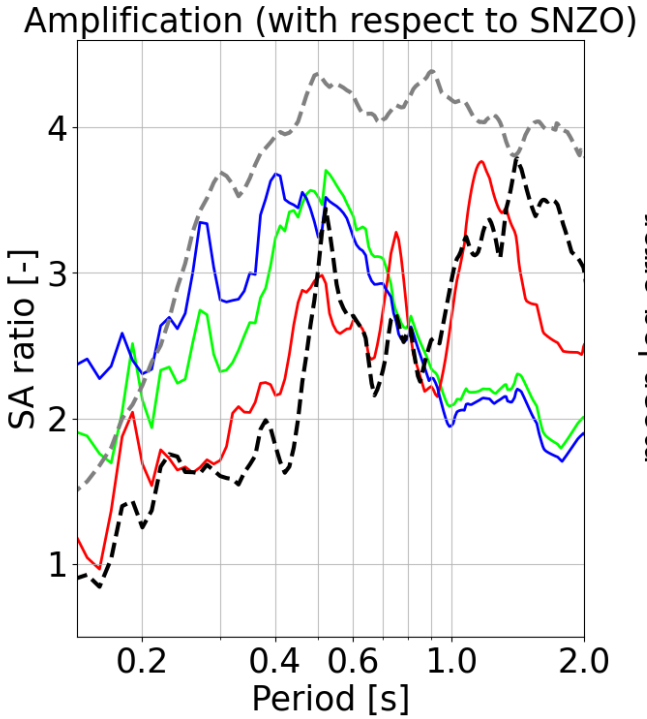


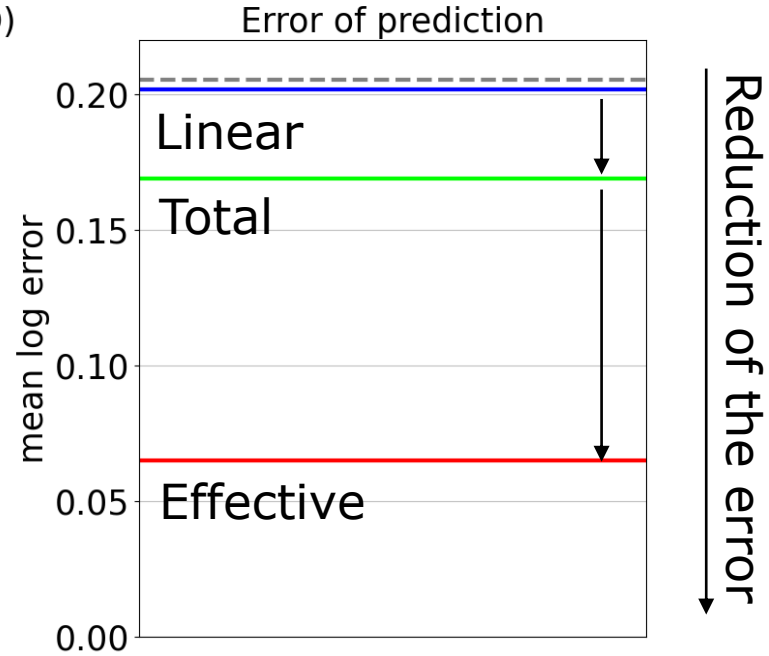
GOOD FIT!

Improvement of the prediction

2013 Cook Strait earthquake (M_w **6.6**), site: PIPS







Simulations:

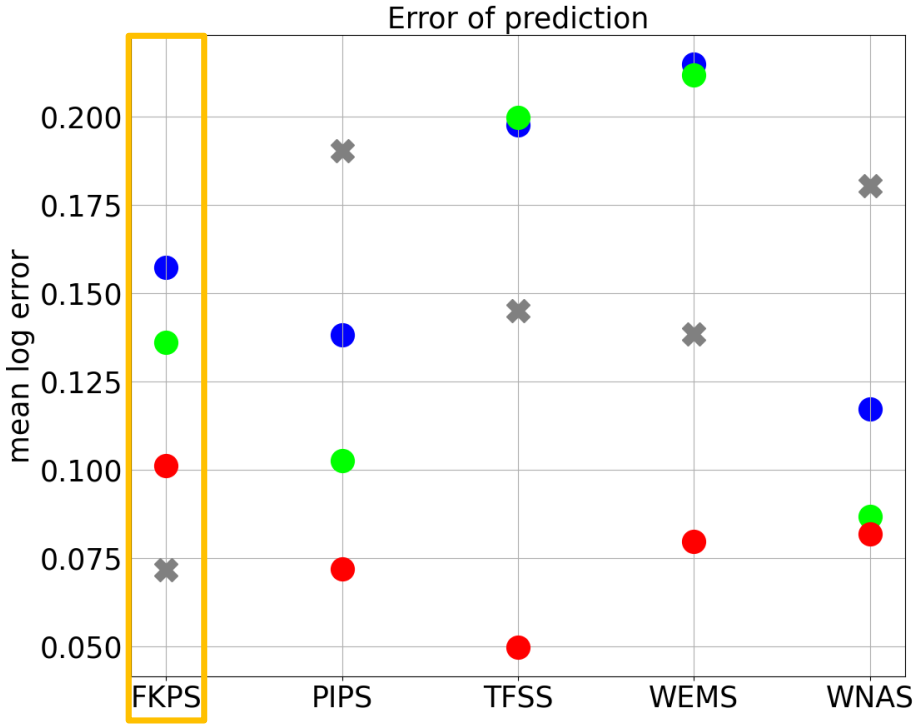
- Linear
- Total stress
- Effective stress

Empirical:

- Observed
- Mean linear amplification

Some overview of the results

2016 Kaikōura earthquake (M_w **7.8**)

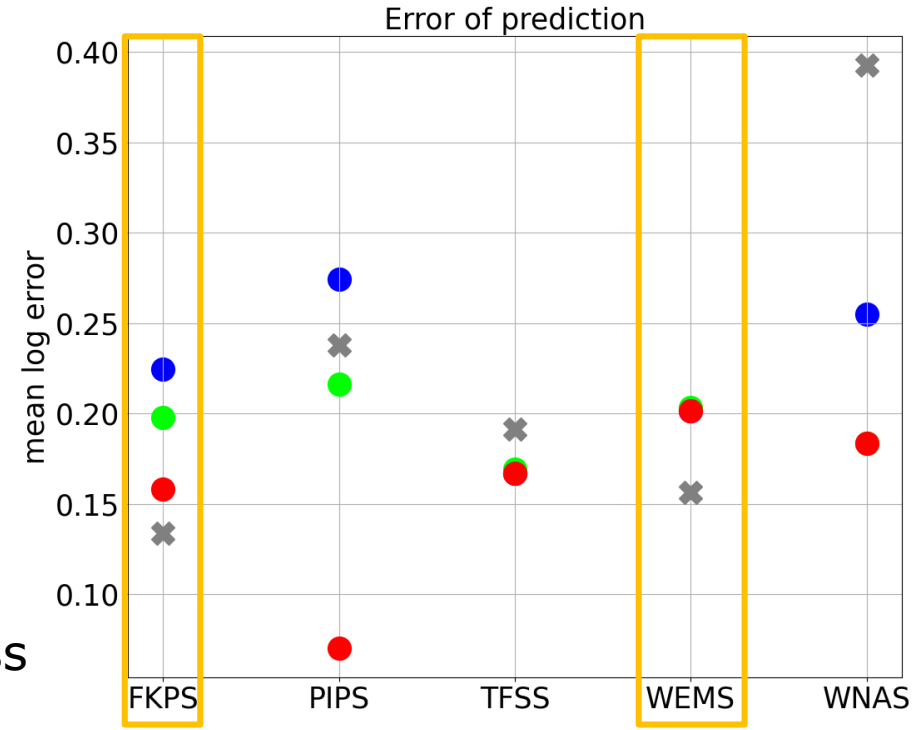


Improvement

Empirical:
- Mean linear

Simulations:
- Linear
- Total stress
- Effective stress

2013 Cook Strait earthquake (M_w **6.6**)



Effective stress simulations:
- generally the best
- better than empirical

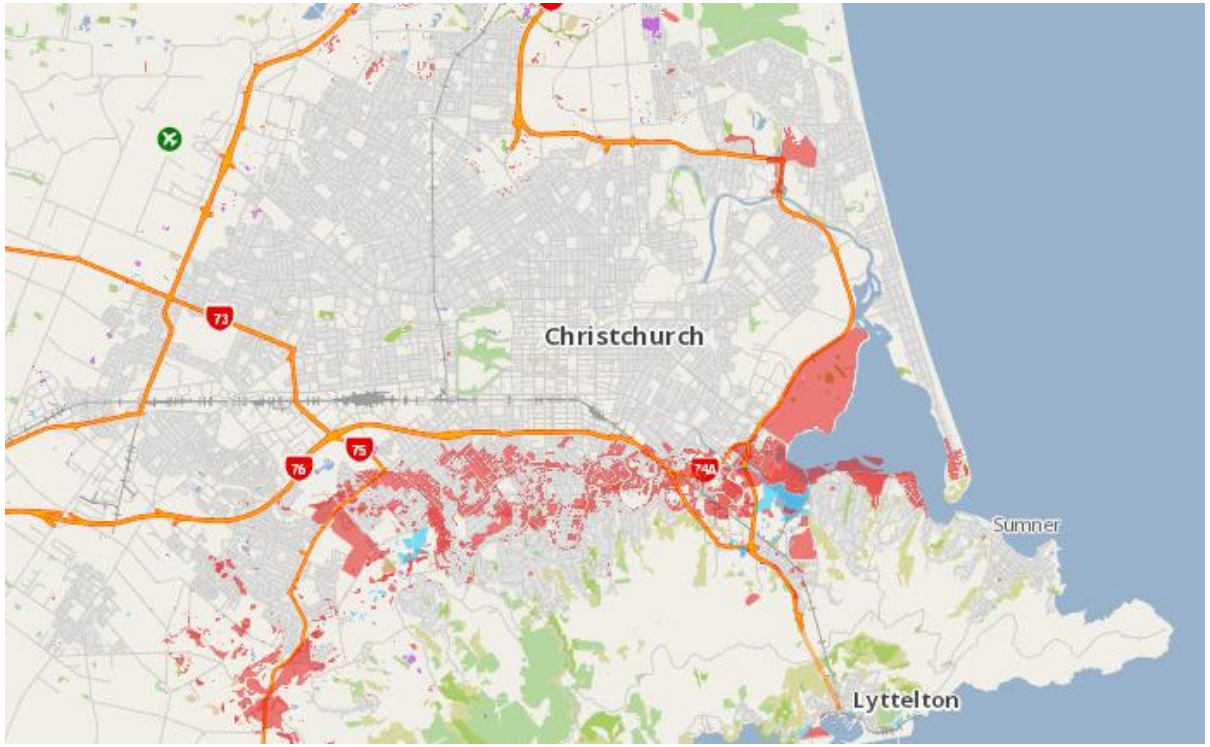
Unsuccessful – only a few cases

What's next?

Some ideas:

- **More sites** in Wellington
- Sites from **Christchurch**
- Why prediction was **unsuccessful** sometimes?
- Comparison to **other predictions** (e.g. linear equivalent)

Christchurch: liquefaction in 2011



canterburymaps.govt.nz

Conclusions

Summary

Multi-step procedure for estimating nonlinear soil response in low seismicity areas

Advantages:

- **site-specific** (based on **CPT** data)
- no need for laboratory or strong motion data
- suitable in **low-seismicity** areas
- both **total** and **effective stress**

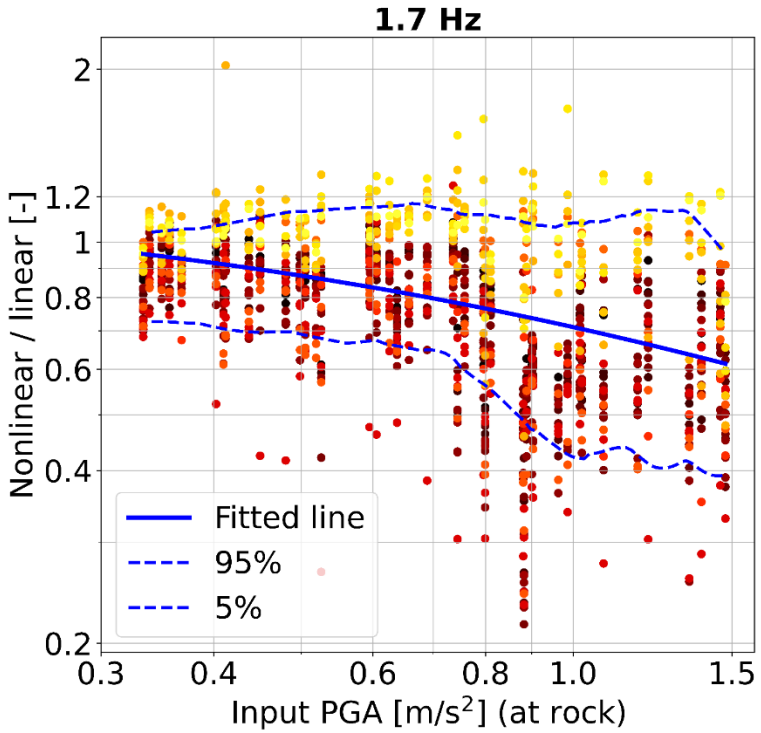
Verification (ongoing)**:** **Wellington** – promising results

Challenges:

- **1D** modelling
- **uncertainty** (soil parameters, input motions)

Lucerne area:

- **strong nonlinearity**
- possible **liquefaction**



Funding and references

URBASIS-EU

HORIZON 2020

Bundesamt für Umwelt BAFU
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Ufficio federale dell'ambiente UFAM
Uffizi federal d'ambient UFAM

Eidgenössisches Nuklearsicherheitsinspektorat ENSI
Inspection fédérale de la sécurité nucléaire IFSN
Ispettorato federale della sicurezza nucleare IFSN
Swiss Federal Nuclear Safety Inspectorate ENSI

ETH zürich

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

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Funding and references

URBASIS-EU

HORIZON 2020

Bundesamt für Umwelt BAFU
Office fédéral de l'environnement OFEV
Ufficio federale dell'ambiente UFAM
Uffizi federal d'ambient UFAM

Eidgenössisches Nuklearsicherheitsinspektorat ENSI
Inspection fédérale de la sécurité nucléaire IFSN
Ispettorato federale della sicurezza nucleare IFSN
Swiss Federal Nuclear Safety Inspectorate ENSI

ETH zürich

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

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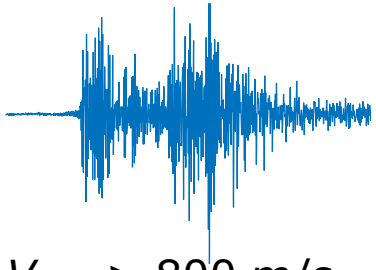
Extra slides

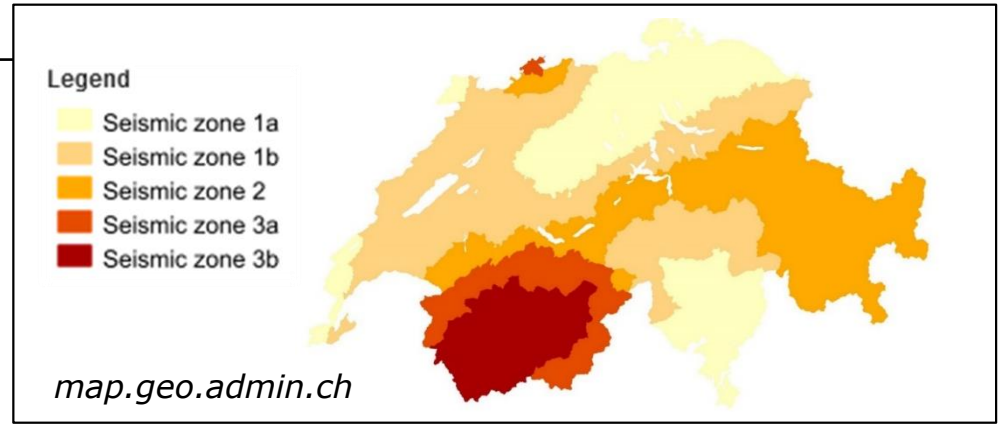
Methodology: input ground motions

Sets of **11 scaled waveforms** (Panzera et al., 2024) compatible with the **elastic response spectrum** for **soil class A** (SIA261, 2020)

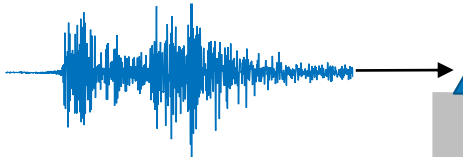
for each zone



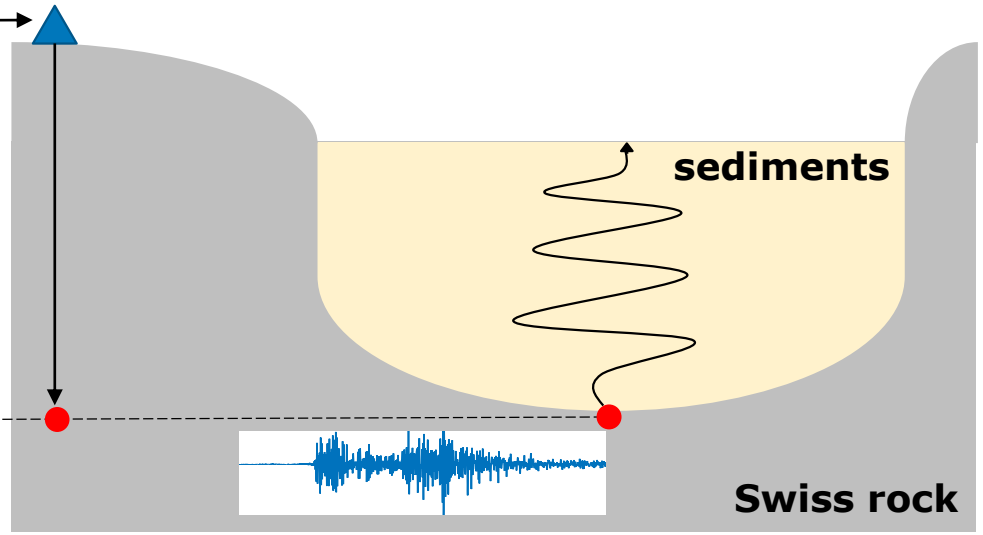
V_{S30} > 800 m/s



Correction for Swiss rock conditions (Poggi et al. 2011) – division by **1.6**



V_{S30} = 1100 m/s



Prediction of **ground motion at depth** (Hallo et al. 2022)

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Methodology: inversion for dilatancy parameters (Roten, 2014)

Dilatancy parameters (Iai et al. 1990)

1. Identifying **liquefaction prone** layers
   (= sandy and saturated)

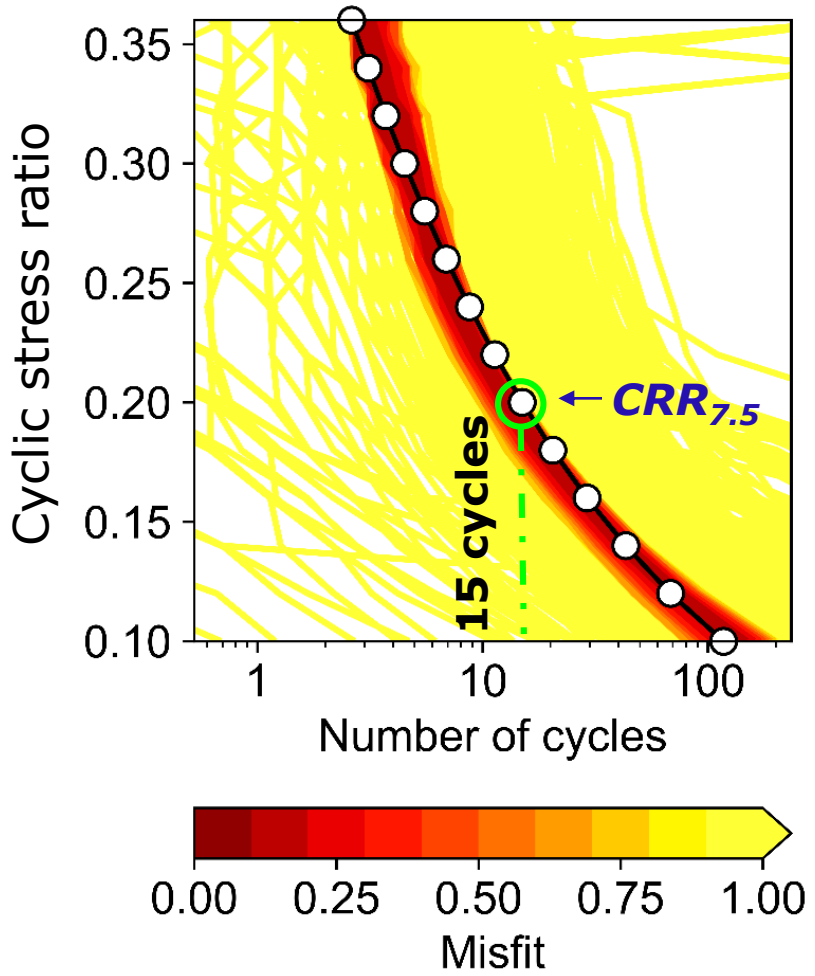
2. **Cyclic resistance ratio** (***$CRR_{7.5}$***) from **CPT**

3. **Liquefaction resistance curve** (**LRC**)

4. Inversion using **Neighbourhood Algorithm**

Forward model: **stress-controlled** simple shear experiment

Liquefaction resistance curves



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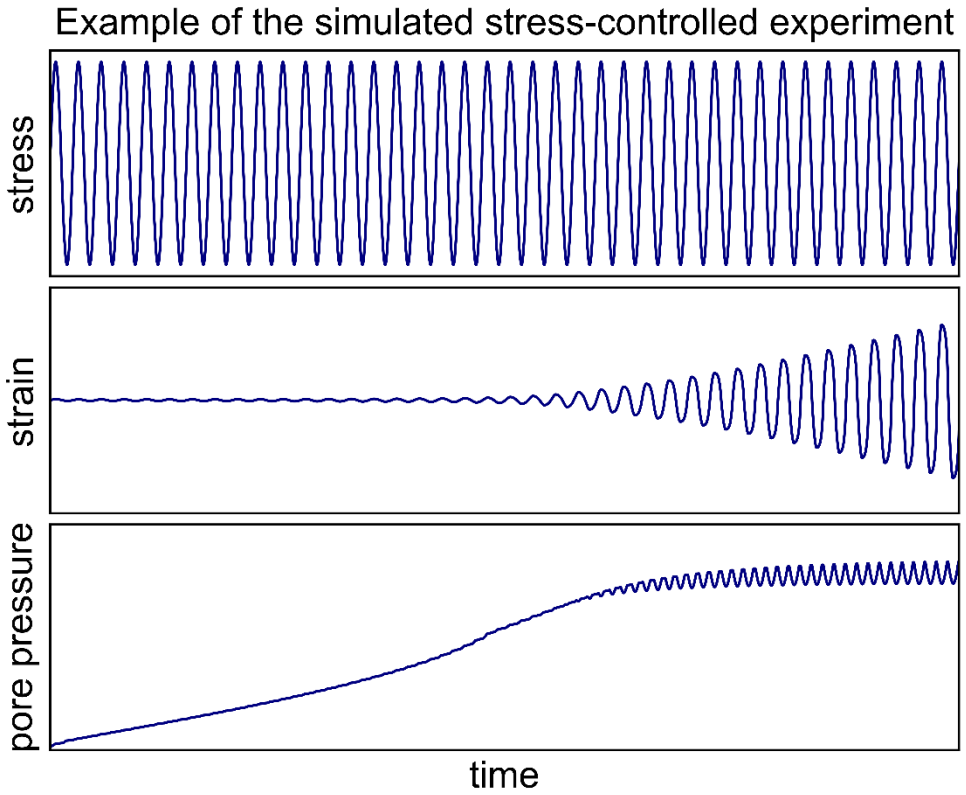
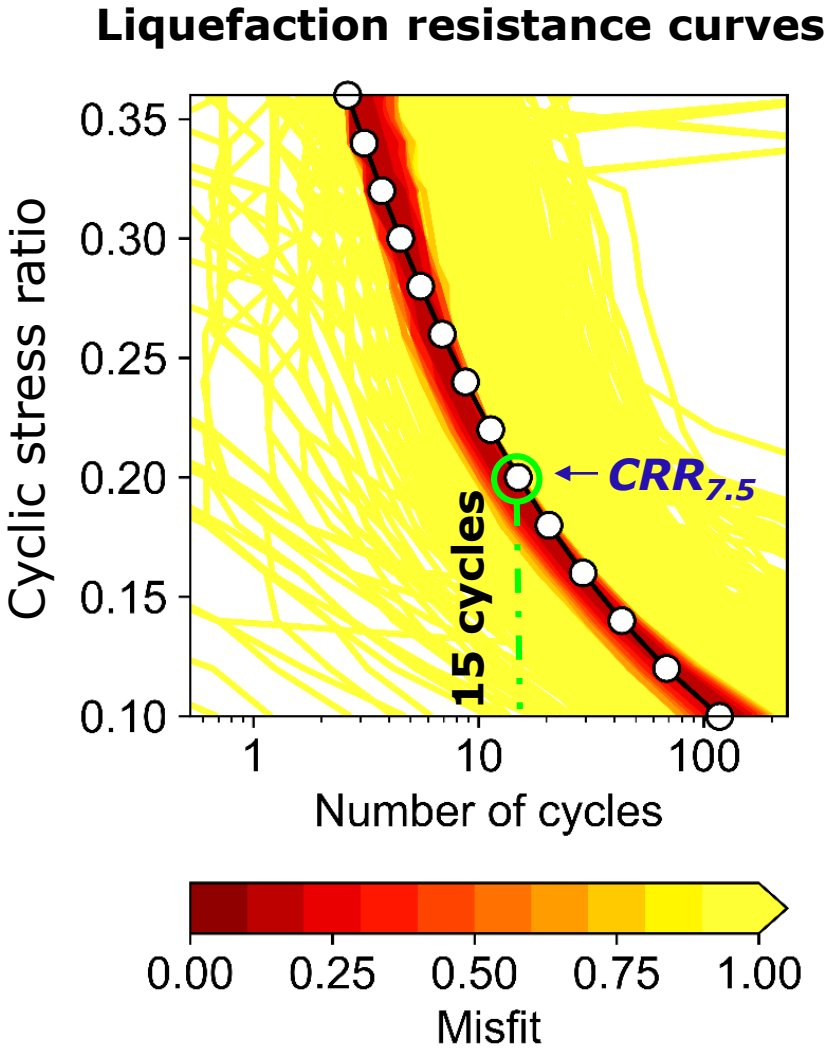
Methodology: inversion for dilatancy parameters (Roten, 2014)





4. Inversion using **Neighbourhood Algorithm**

Forward model: **stress-controlled** simple shear experiment

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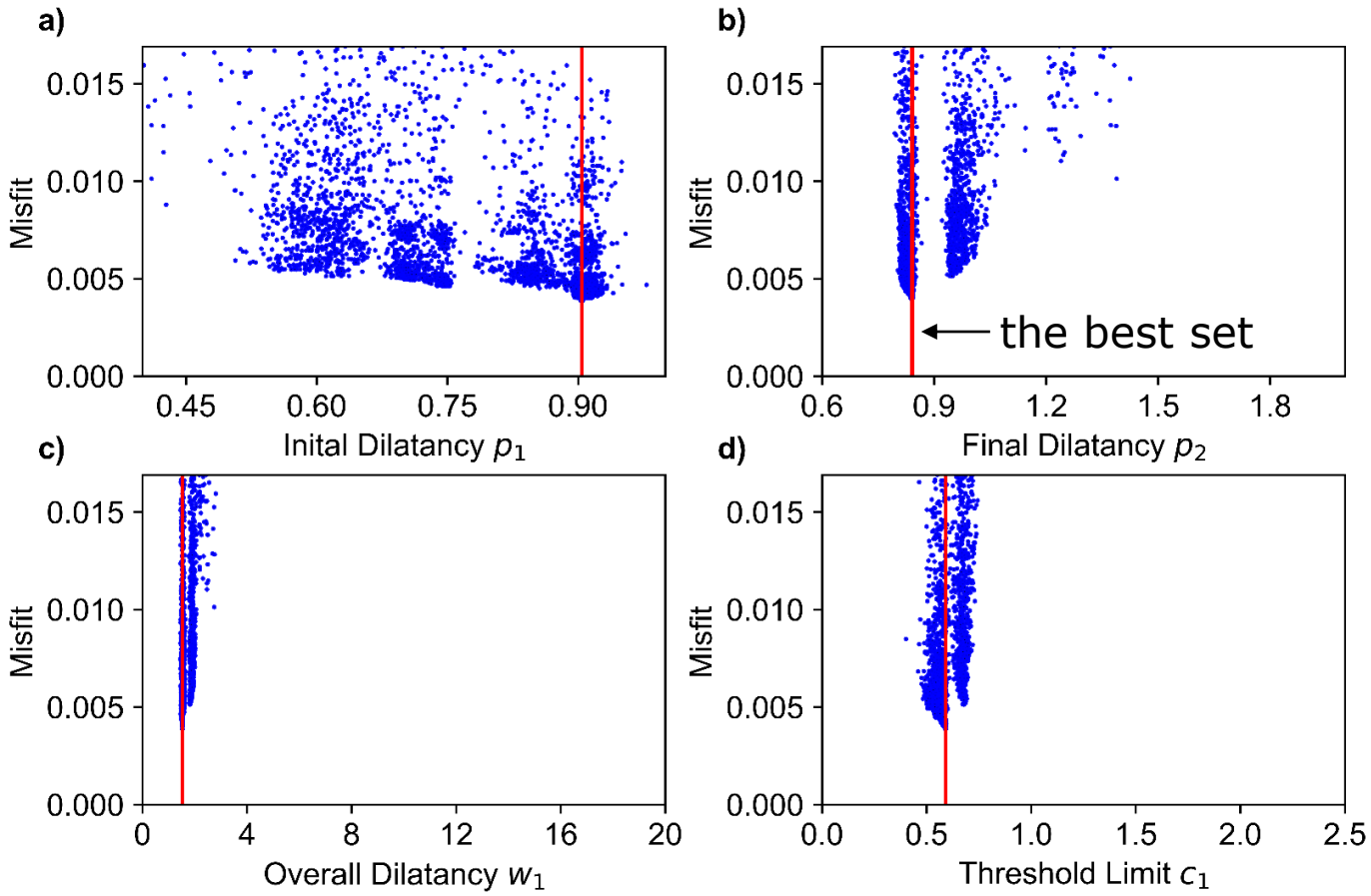
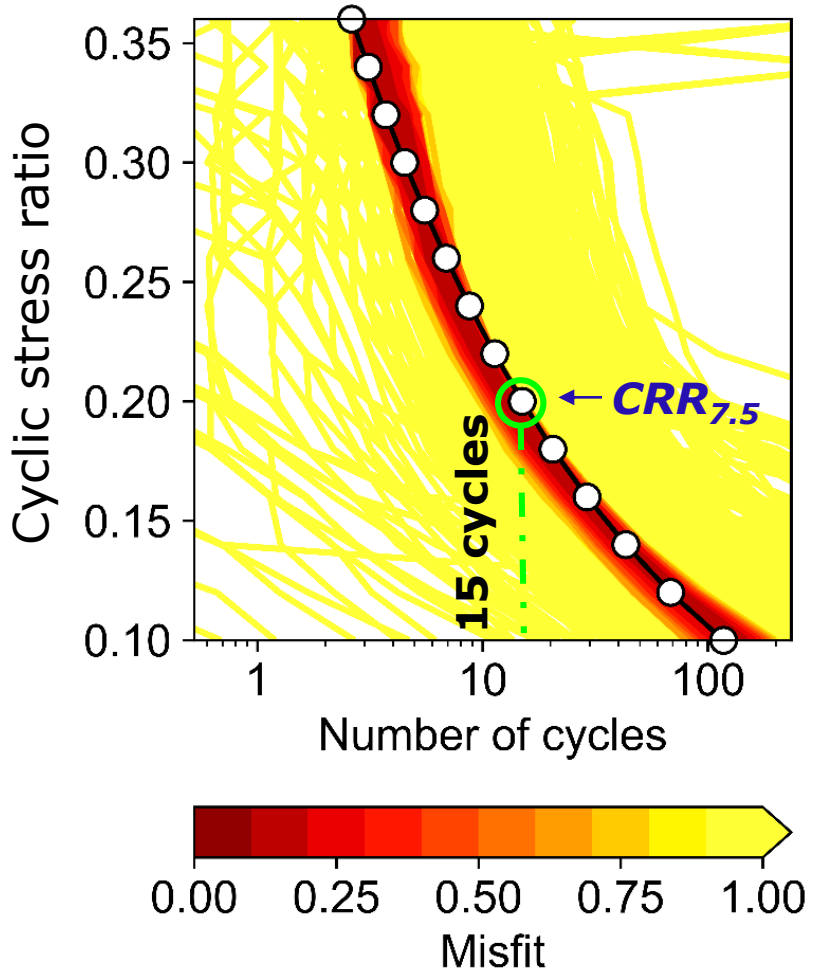
Methodology: inversion for dilatancy parameters (Roten, 2014)

Nonlinear and **non-unique** problem



tested sets of dilatancy parameters

Liquefaction resistance curves



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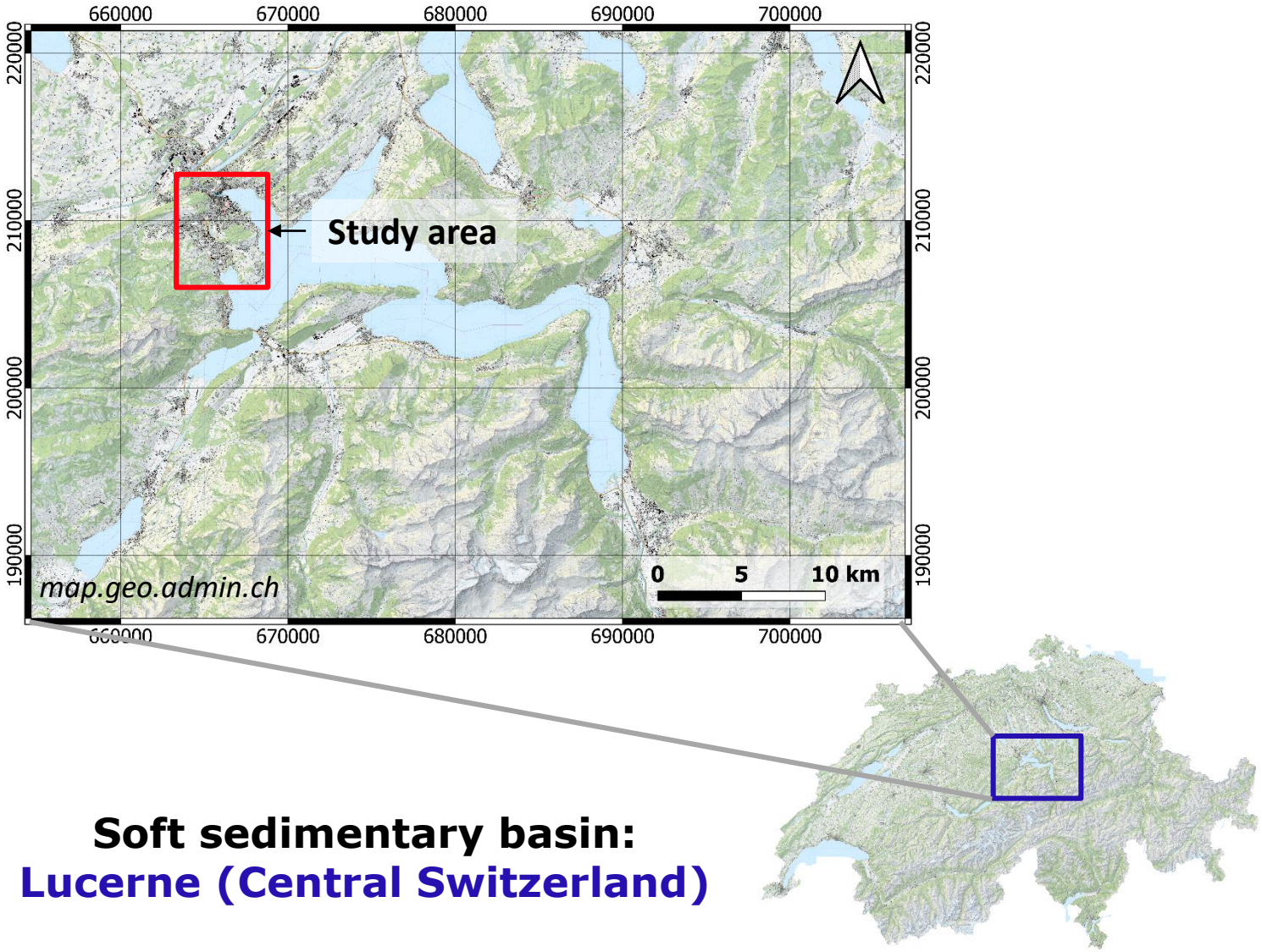
Lucerne: location



Soft sedimentary basin:
Lucerne (Central Switzerland)

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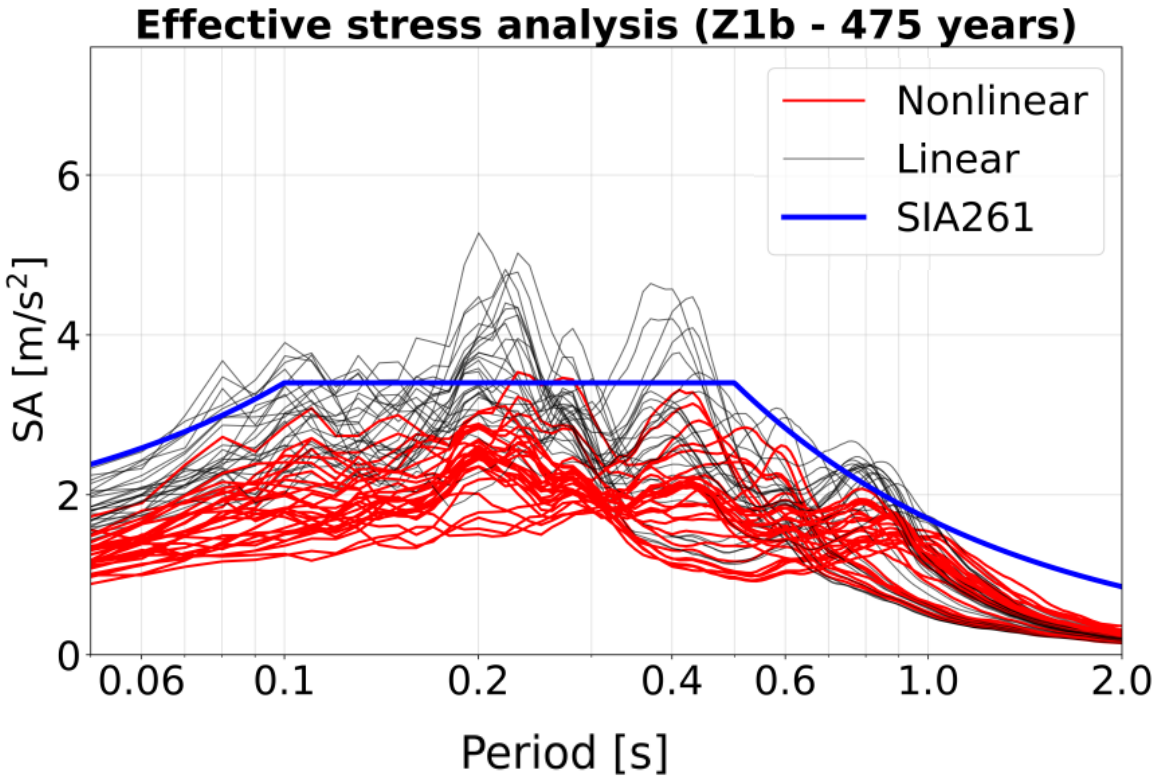
Lucerne: variability

(29 sites, 11 input motions for 475 yr return period)

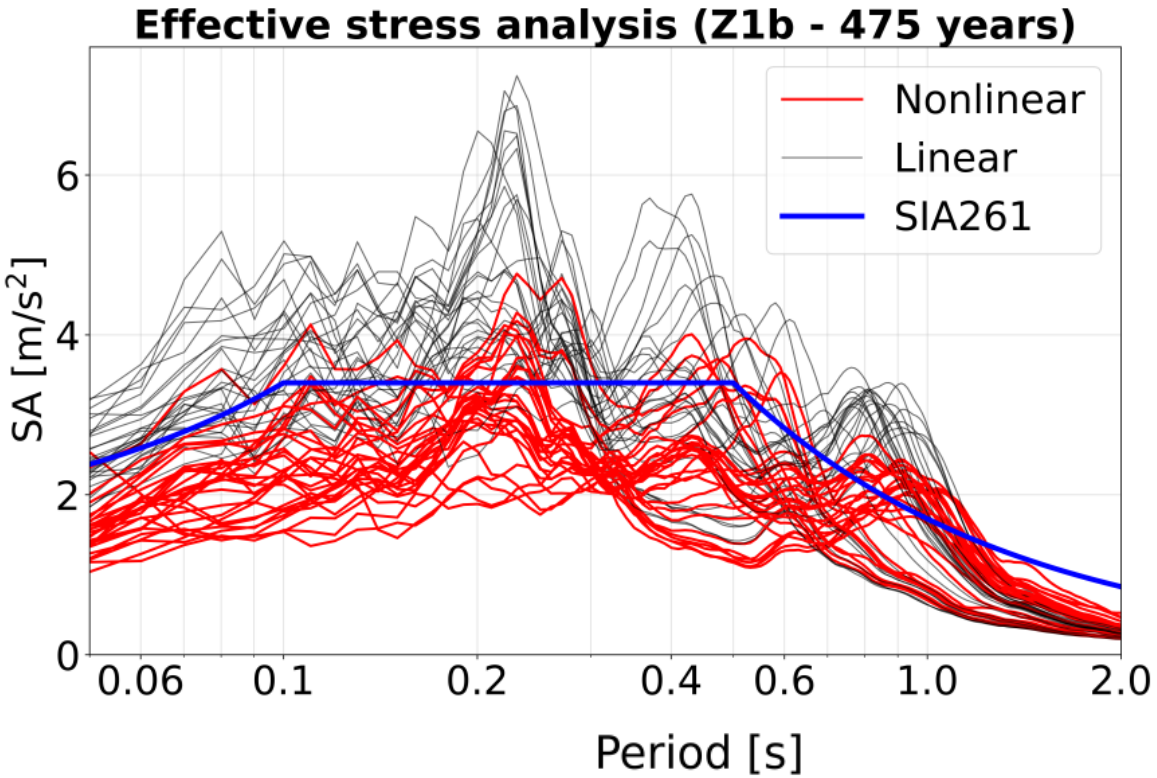
SIA261 (2020)
design spectrum from
Swiss building code

Response spectra (1D)

Mean for each site



Mean + standard deviation for each site



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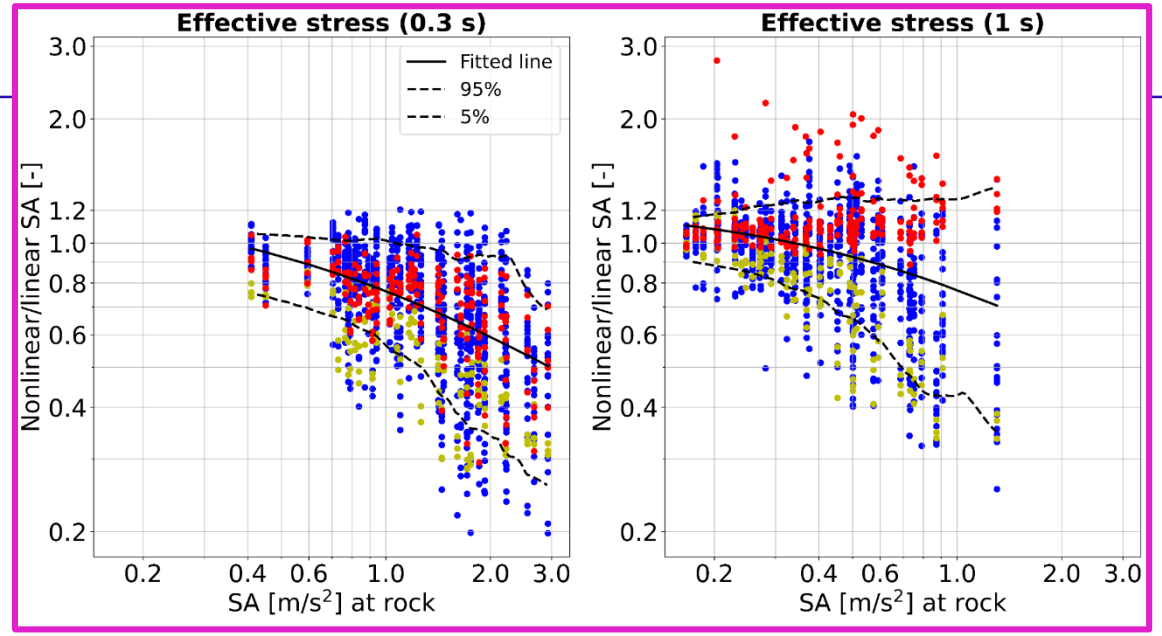
Lucerne: variability

29 sites
44 input motions (different hazard levels)
effective and total stress

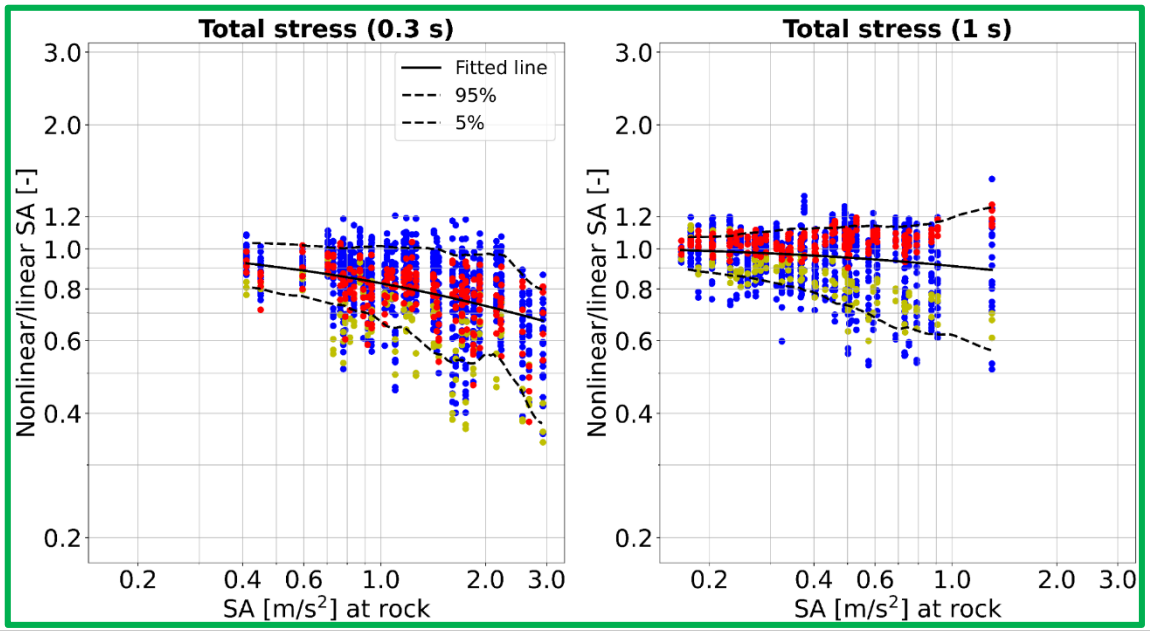
Effective vs **total** **stress** analysis



Nonlinearity and **liquefaction**

Some correlations with:

- f_0
- water table depth
- bedrock depth
- soil classes →



Soil class:

- **D**
- **E**
- **F**

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Lucerne: liquefaction potential

Liquefaction onset in at least one layer

high

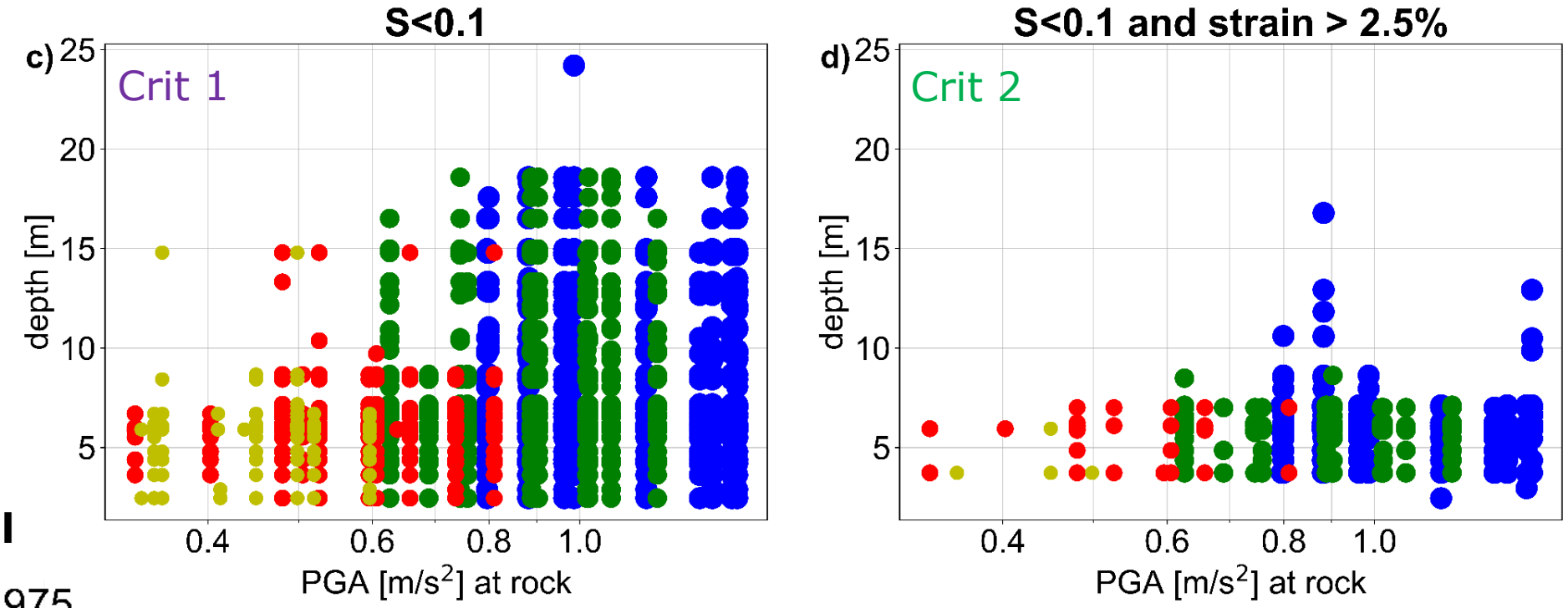
low

Hazard level	% of sites (29 sites)	
11 waveforms	Crit 1	Crit 2
Zone Z2 – 975 years	97%	72%
Zone Z1b – 975 years	97%	52%
Zone Z1b – 475 years	79%	28%
Zone Z1a – 475 years	62%	7%

Criterion 1 – 90% reduction of initial confining stress
Criterion 2 – 90% reduction of initial confining stress + strain>2.5%

Lucerne: liquefaction potential

Depth of the layer were liquefaction onset is simulated



Hazard level

high

low

- Z2 - 975
- Z1b - 975
- Z1b - 475
- Z1a - 475

(S – reduction of initial confining stress)

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Lucerne: comparison to Japanese Kik-net data

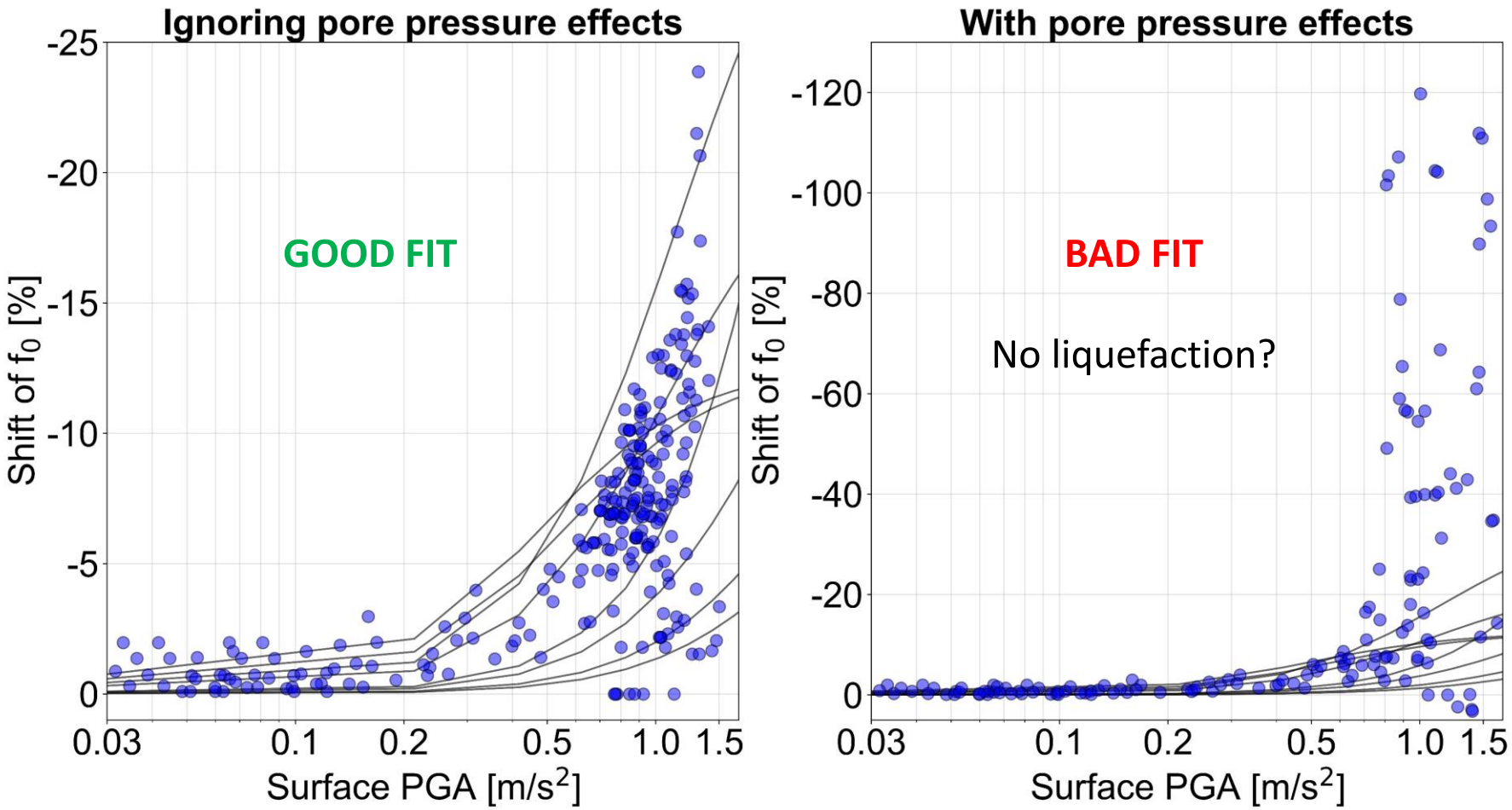
Kik-net station ——

Correlations based on many events (Loviknes et al. 2022)

Lucerne ●

Each point = one simulation

Shift of fundamental frequency



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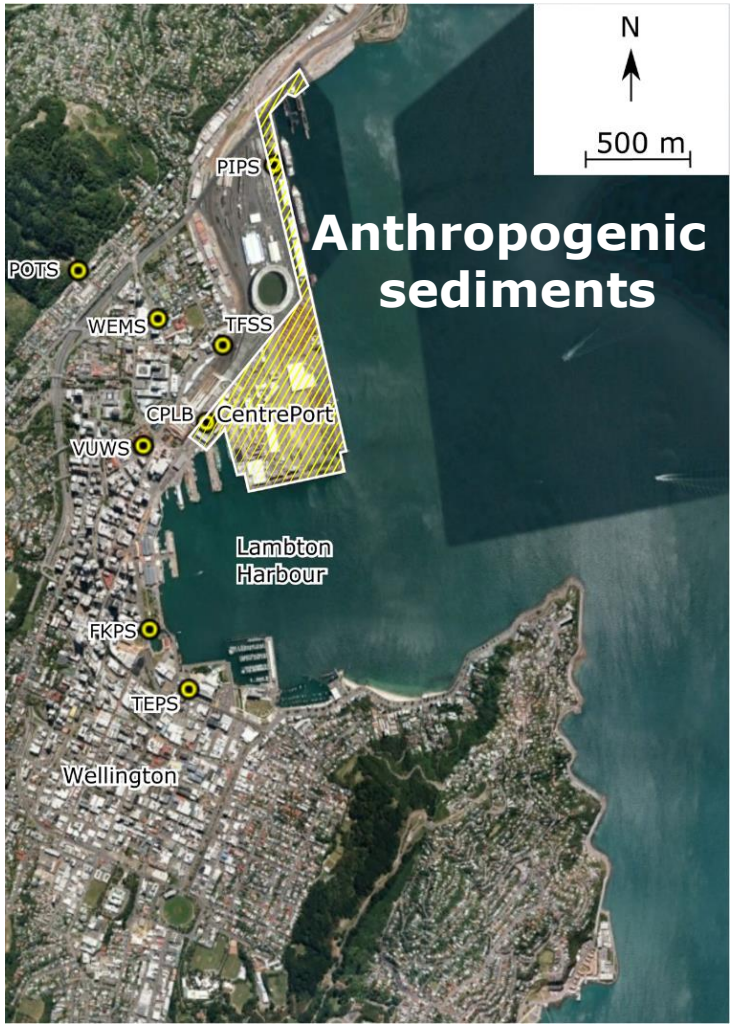
Wellington: Observed damage due to liquefaction

CentrePort, Wellington



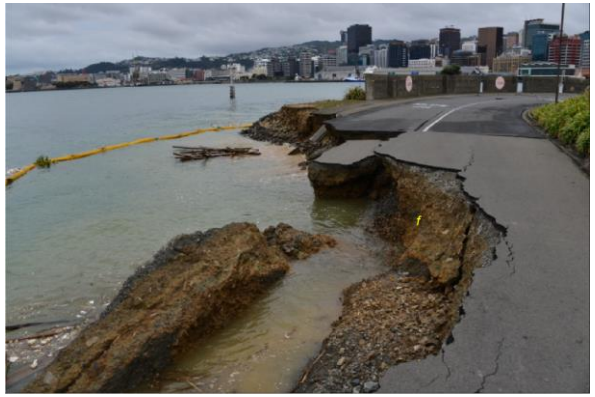
Cubrinovski et al (2018)

2016 Kaikōura earthquake (M_w **7.8**)

Cubrinovski et al (2018)

strong motion stations

2013 Cook Strait earthquake (M_w **6.6**)



Hancox et al (2013)

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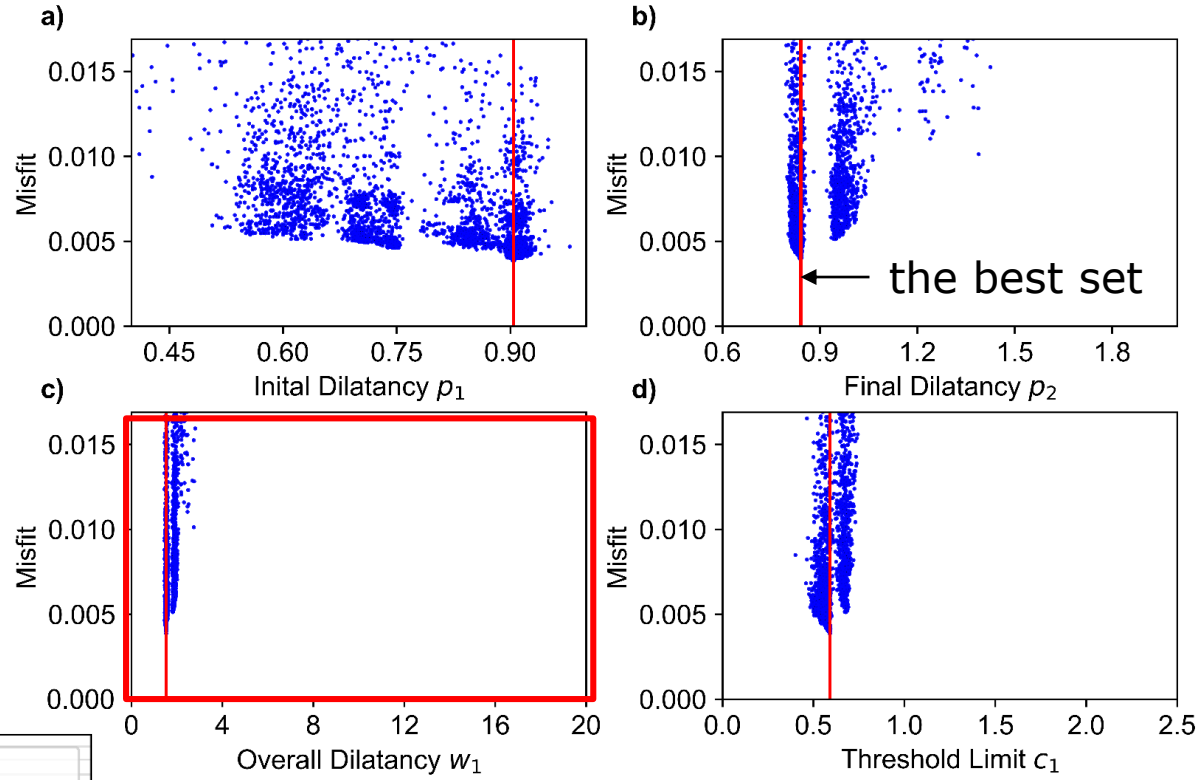
Sensitivity: dilatancy parameters

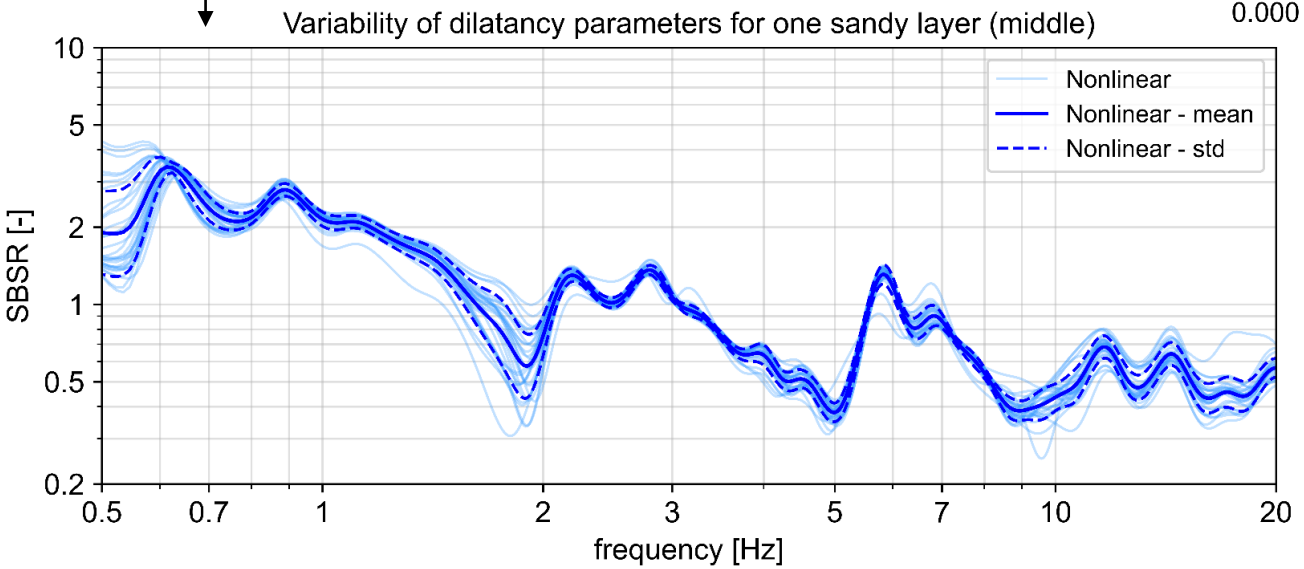
Inversion:

Nonlinear and **non-unique** problem →



Simulations:

Small influence...



tested sets of dilatancy parameters

← **30 sets** of dilatancy parameters

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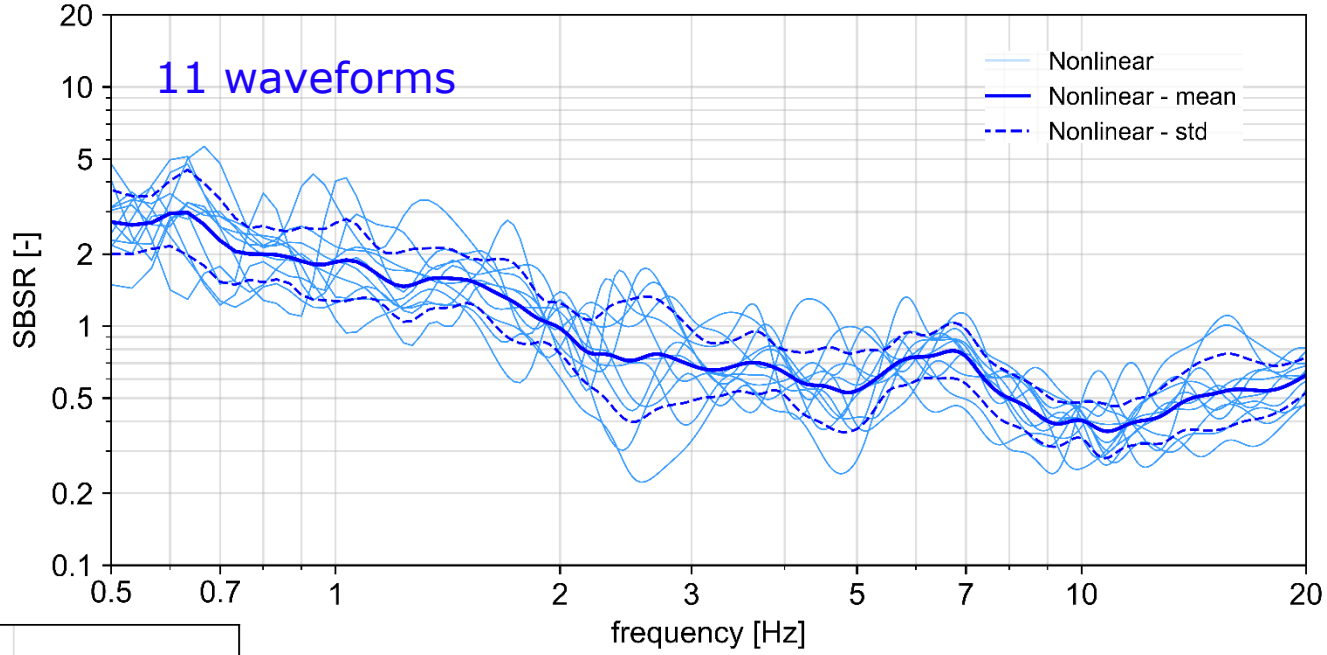
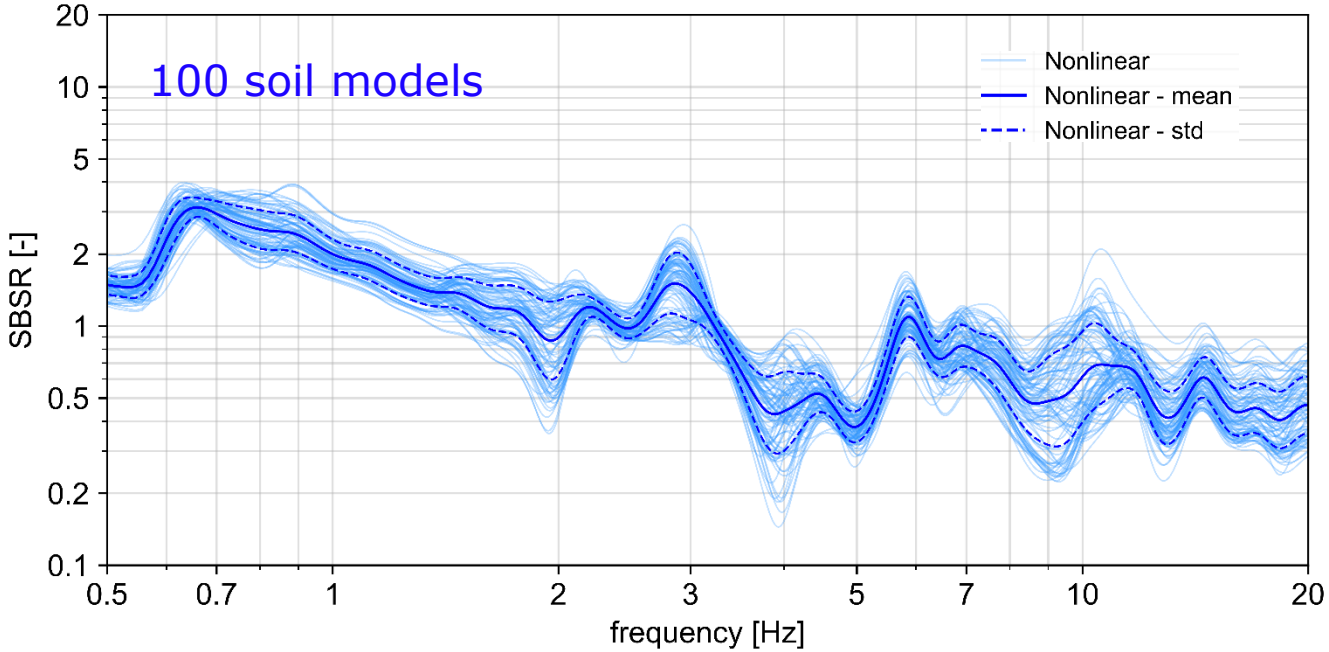
Sensitivity

Variability due to:

- **Input waveforms**
- Different **soil model parameters**





Significant **variability**

Uncertainty of estimation

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