# Modelling soil response at the national scale for Switzerland in the framework of risk assessment of induced seismicity

**Paolo Bergamo***[1], Jaleena Sunny[1], Iason Grigoratos[1], Philippe Roth[1], Toni Kraft[1], Francesco Panzera[2], and Stefan Wiemer[1]

[1]Swiss Seismological Service (SED), ETH Zürich, Switzerland

[2]Department of Biological, Geonological and Environmantal Science, University of Catania, Catania, Italy

*paolo.bergamo@sed.ethz.ch

# 1) Motivation 2) IERM-CH25 risk model 3) Soil response model 4) Testing

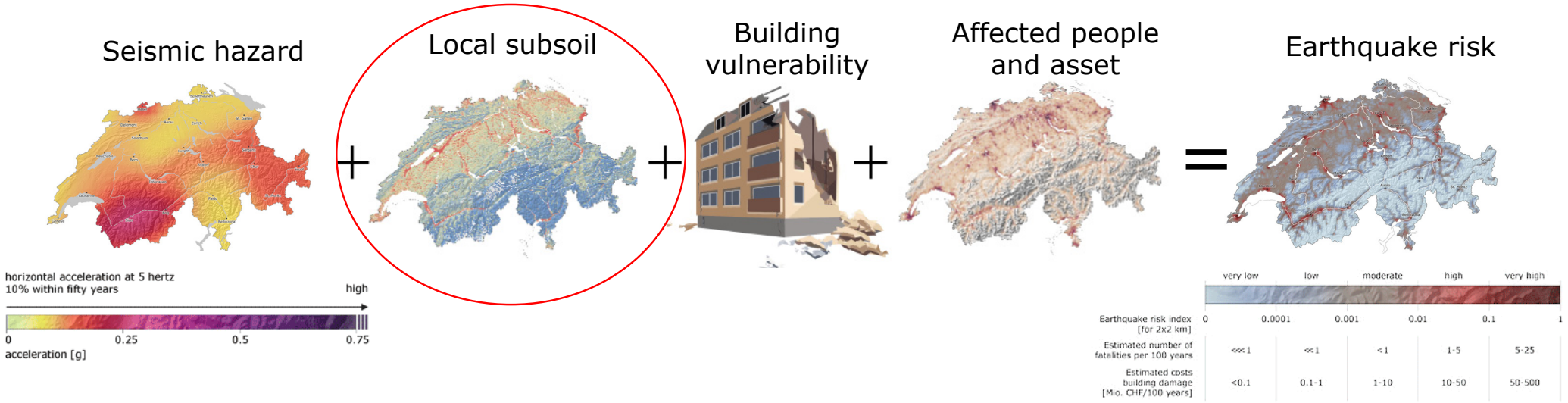
what is earthquake risk modeling and what are the benefits it brings?

Earthquake risk modeling is a process used to assess and quantify the potential impacts of earthquakes on a given area or structure. It involves the integration of various scientific disciplines, including seismology, geology, engineering, and statistics, to estimate the likelihood and consequences of earthquake events. Here are the key components and benefits of earthquake risk modeling:

**Benefits:**

1. **Informed Decision-Making**: Risk models provide valuable insights for urban planners, policymakers, and emergency managers, helping them make informed decisions about land use, building codes, and disaster preparedness.
2. **Risk Mitigation**: By identifying high-risk areas and vulnerable structures, risk models can guide mitigation efforts, such as retrofitting buildings or improving infrastructure, to reduce potential losses.
3. **Insurance and Financial Planning**: Insurance companies use risk models to set premiums and manage their portfolios. Governments and businesses can also use these models for financial planning and risk management.
4. **Public Awareness and Preparedness**: Risk models can raise public awareness about earthquake risks and promote preparedness, potentially saving lives and reducing injuries.
5. **Emergency Response Planning**: Understanding potential impacts helps in developing effective emergency response plans, ensuring that resources are allocated efficiently during a disaster.
6. **Resilience Building**: Long-term resilience strategies can be developed based on risk modeling, helping communities recover more quickly from earthquakes.

https://chat.mistral.ai/chat

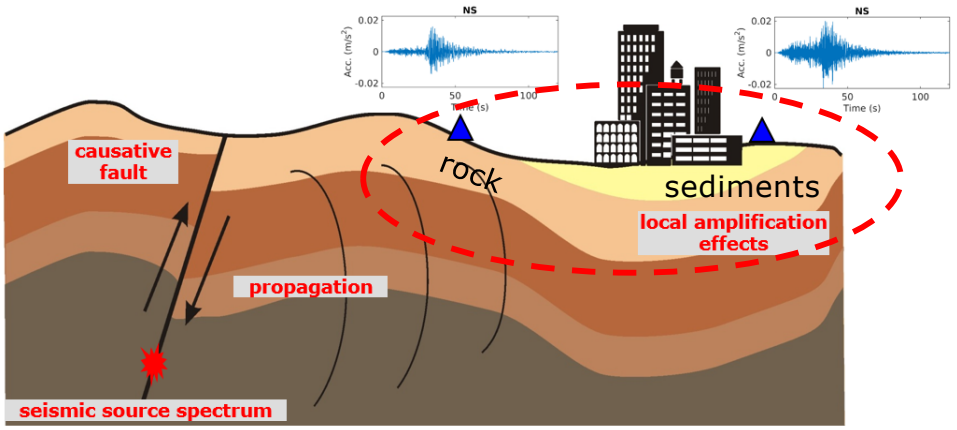



http://www.seismo.ethz.ch/en/earthquake-country-switzerland/risk/overview/

Earthquake Risk Model Switzerland ERM-CH23 (Wiemer et al. 2023): first publicly available earthquake risk model for Switzerland

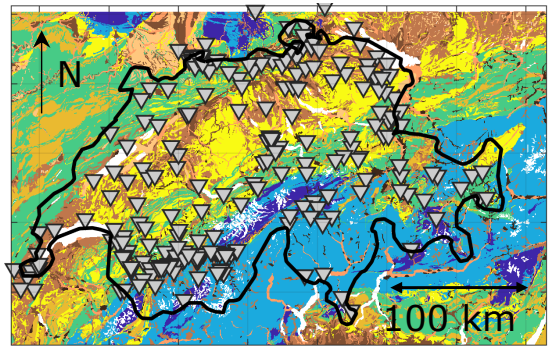
# 1) Motivation 2) IERM-CH25 risk model 3) Soil response model 4) Testing

Why is soil amplification important in risk assessment?




*from Ciaccio & Cultrera (2014)*

## 1) Wide range of variability

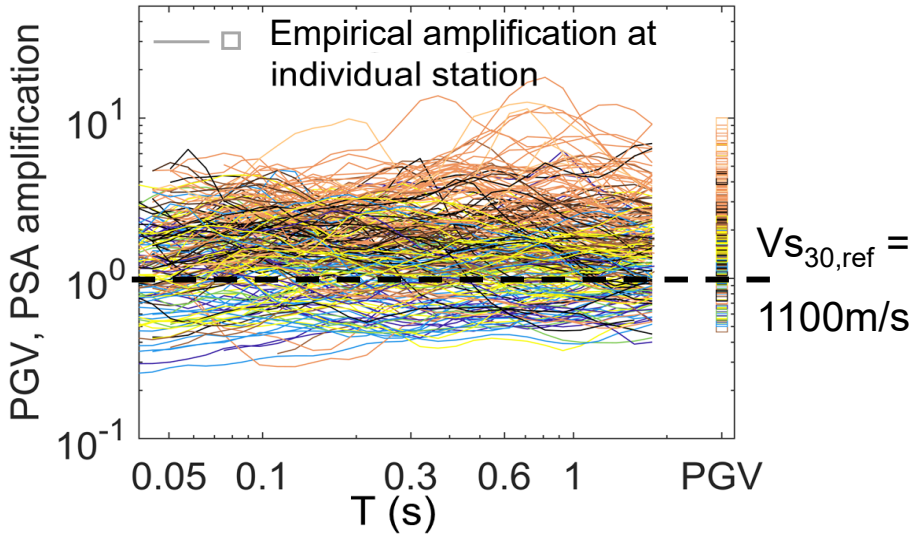



▽ Seismic stations

Lithogroups

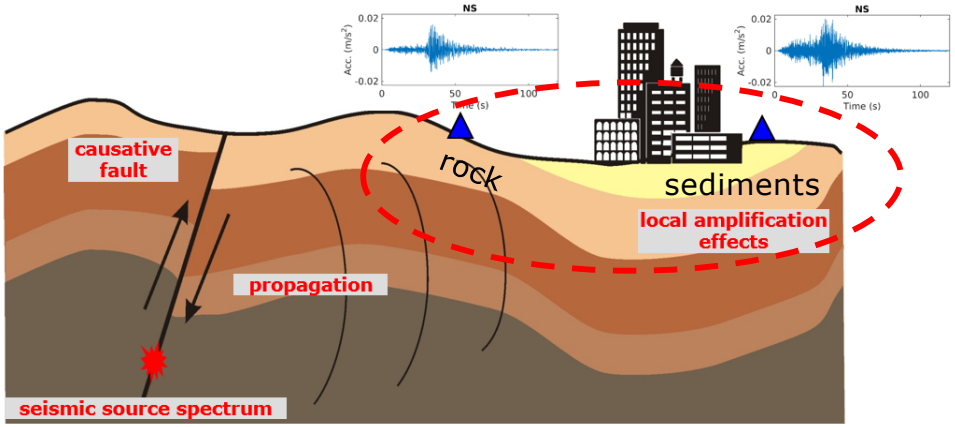
- Fine-grained deposits
- Sand & gravel w. clay or silt
- Sand & gravel
- Silt & sand bodies w. gravel,rocks
- Debris, blocks, shingle
- Sedimentary clastic rocks
- Sed. clastic & biogenic rocks
- Metamorphic rocks
- Magmatic rocks

Softer soil



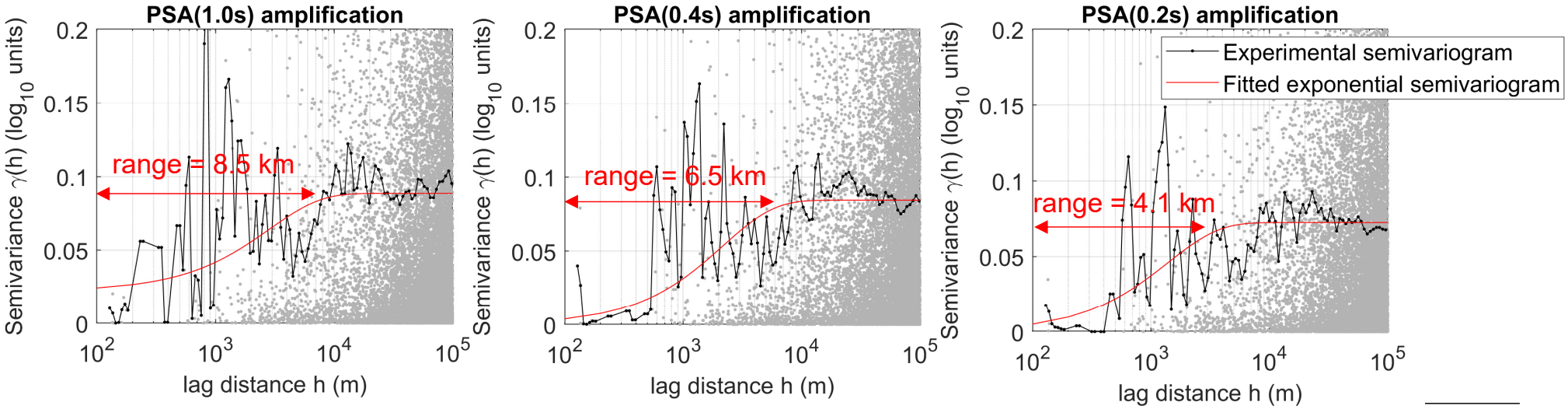
# 1) Motivation 2) IERM-CH25 risk model 3) Soil response model 4) Testing

Why is soil amplification important in risk assessment?



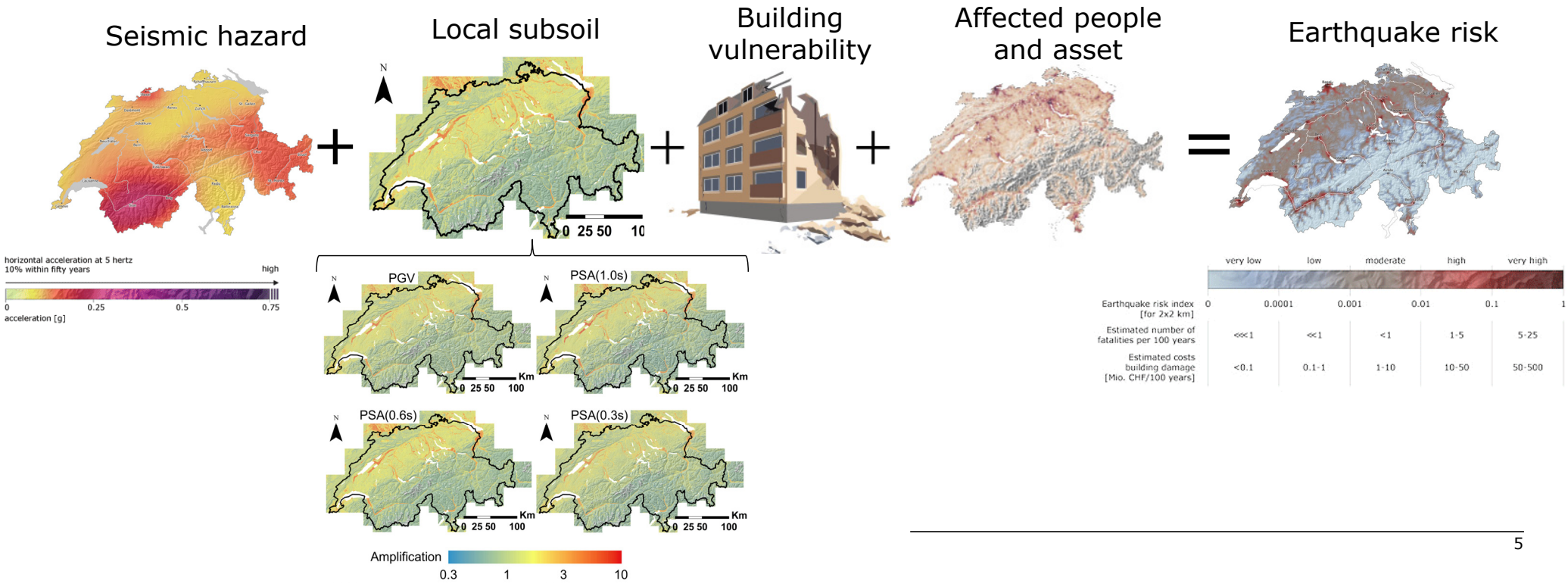

1) Wide range of variability

2) Sharp spatial variability



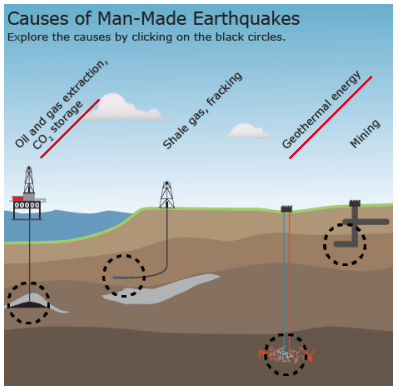
With rising interest in geothermal energy and $CO_2$ injection in Switzerland, the Federal Office of Energy tasked the Swiss Seismological Service to extend the national Earthquake Risk Model (ERM-CH23) to include **shallow induced seismicity (IERM-CH25)**

ERM-CH23

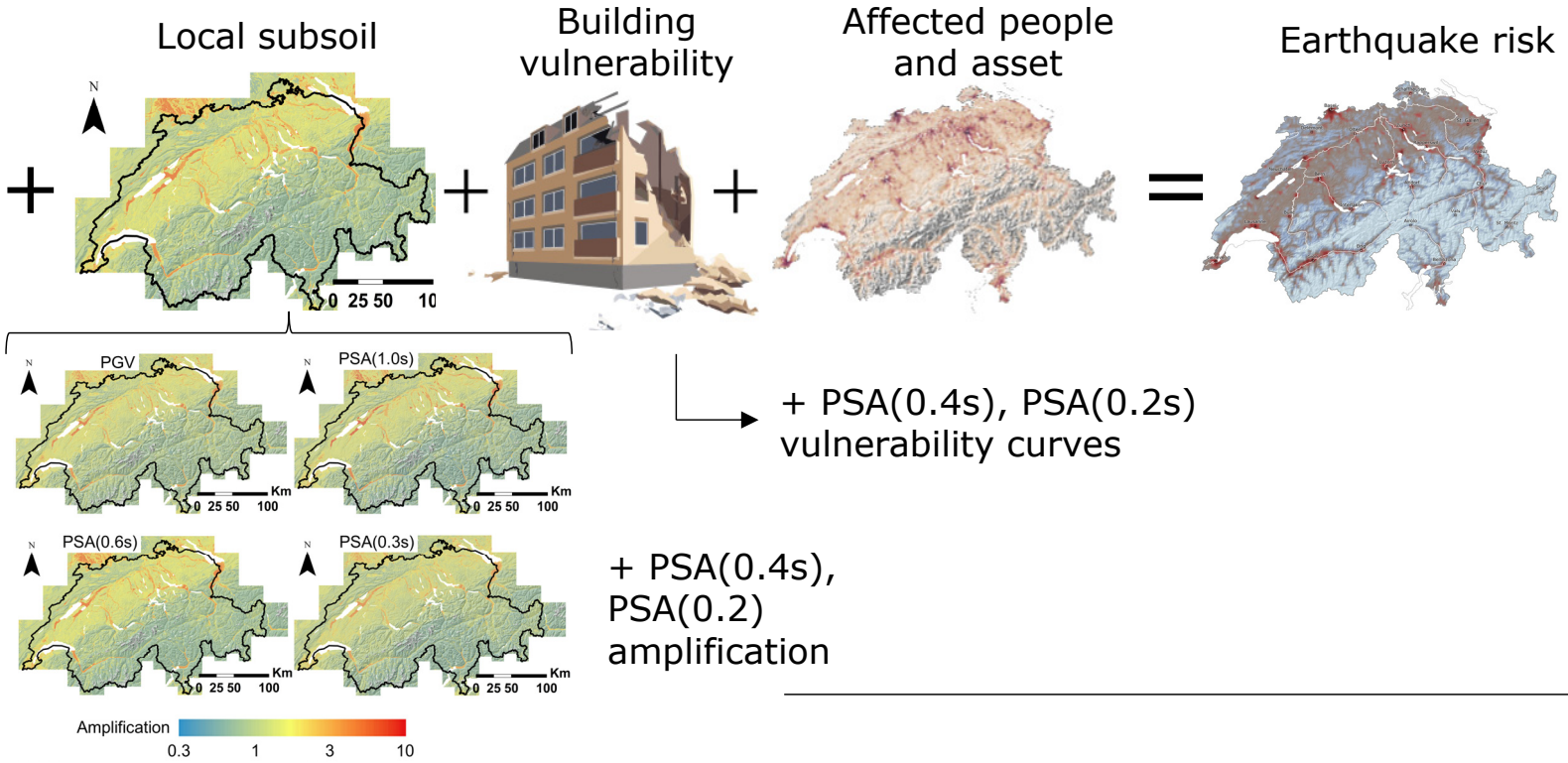


With rising interest in geothermal energy and $CO_2$ injection in Switzerland, the Federal Office of Energy tasked the Swiss Seismological Service to extend the national Earthquake Risk Model (ERM-CH23) to include **shallow induced seismicity (IERM-CH25)**

ERM-CH23 -> IERM-CH25




- Review of $M_{min}$,$M_{max}$
- Review of GM models
- Review of GM logic tree




+ PSA(0.4s), PSA(0.2s) vulnerability curves

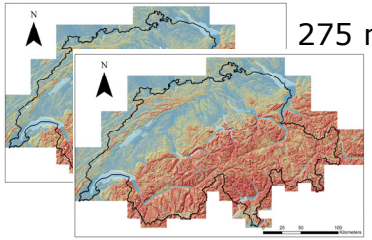
+ PSA(0.4s), PSA(0.2) amplification

# ERM-CH23 soil amplification maps

Multi-scale terrain slope

600 m scale

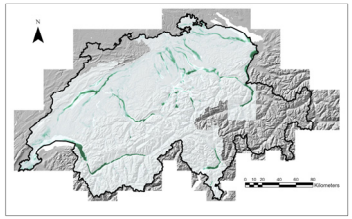
275 m scale



(deg)

0 10 20 30

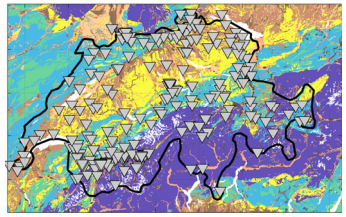
Bedrock-depth model



(m)

0 150 >=300

Lithology

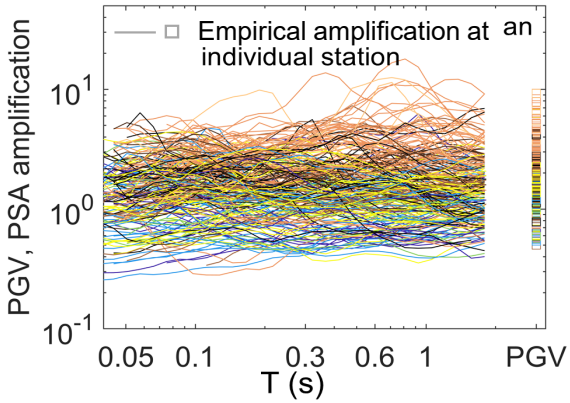


240 seismic stations

Lithogroups

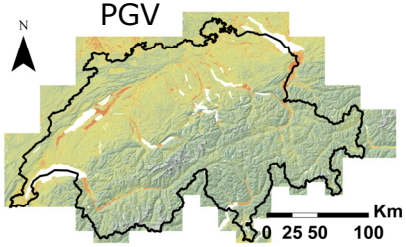
LG1
LG2
LG3
LG4
LG5
LG6
LG7
LG8
LG9

Empirical amplification from seismic stations (2000 – 2022)

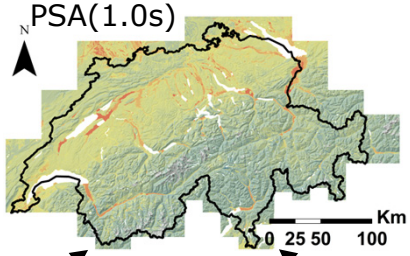



# Regression kriging (RK)

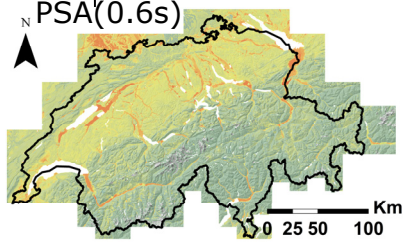
PGV



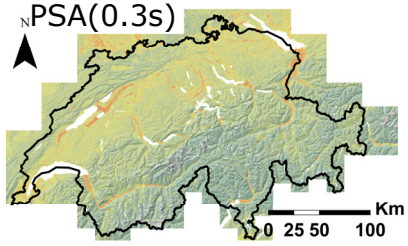

PSA(1.0s)

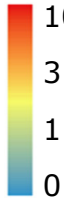



PSA(0.6s)




PSA(0.3s)

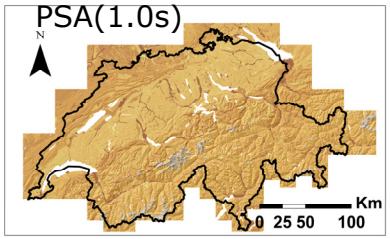


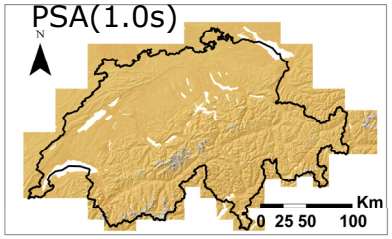

Amplification wrt. $V_{S30}$ = 1100 m/s

Epistemic uncertainty $\varphi_{S2S}$

PSA(1.0s)




PSA(1.0s)

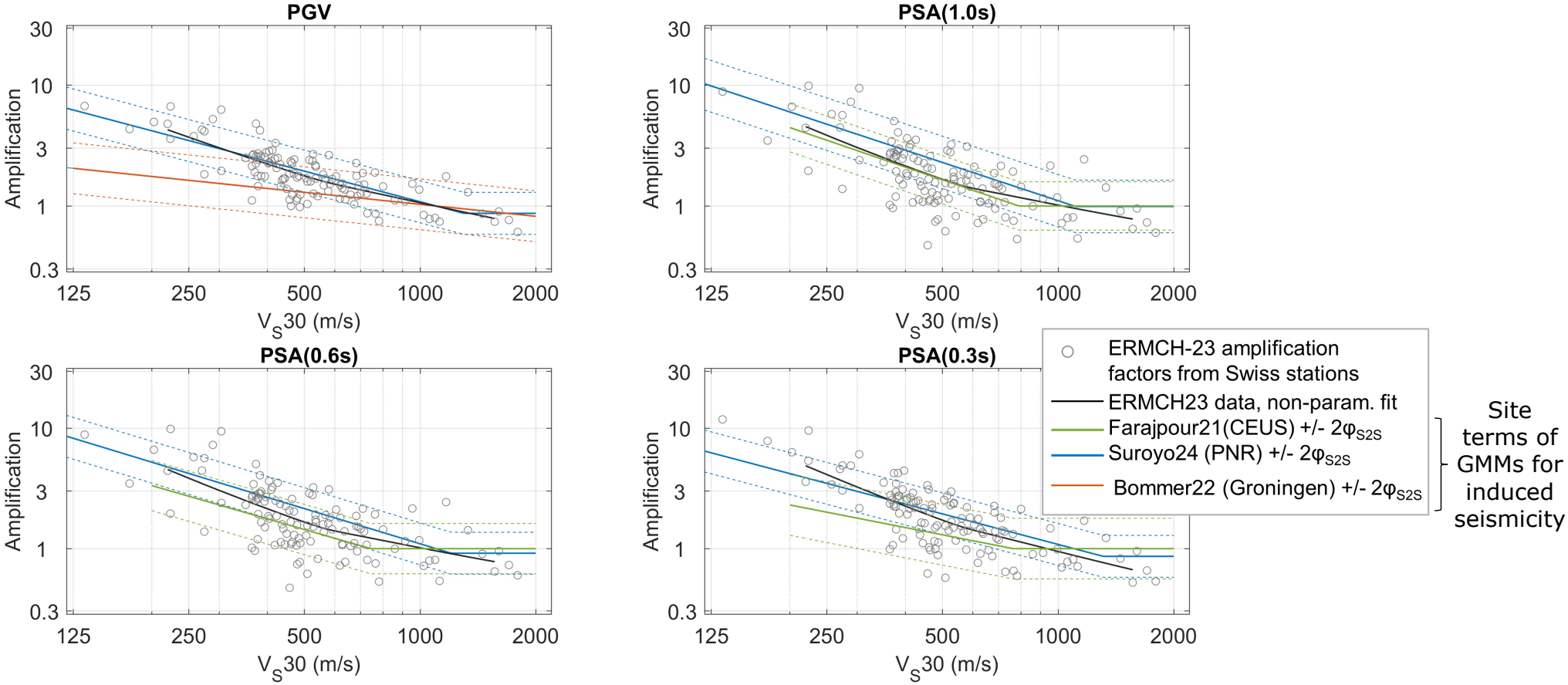



Aleatory variability $\varphi_{SS}$

$\log_{10}$ units

0.05 0.25

# ERM-CH23 soil amplification maps: can we use them for induced seismicity?



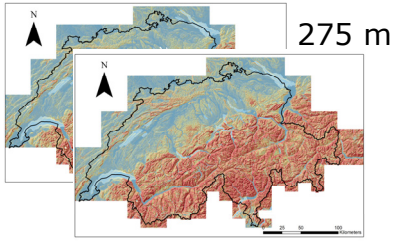

...yes

# ERM-CH23 soil amplification maps

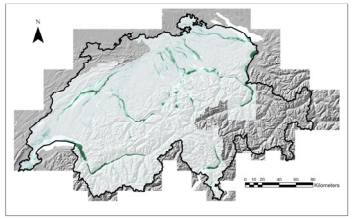
Multi-scale terrain slope

600 m scale

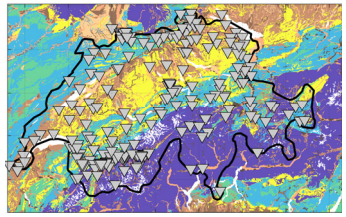
275 m scale




Bedrock-depth model

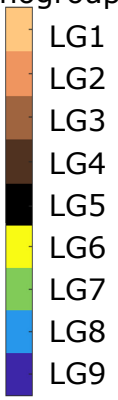



Lithology

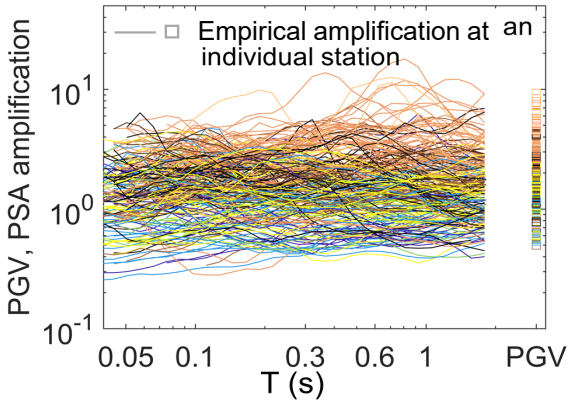


▽ 240 seismic stations

Lithogroups




Empirical amplification from seismic stations (2000 – 2022)



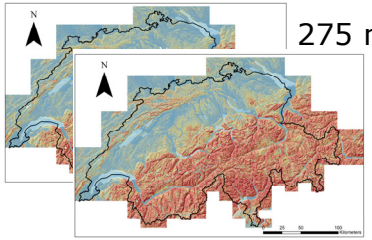

## Regression kriging (RK)

# (additional) IERM-CH25 soil amplification maps

Multi-scale terrain slope

600 m scale

275 m scale



(deg)

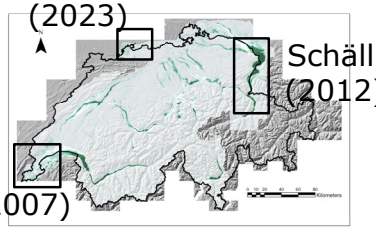
0 10 20 30

Bedrock-depth model

Imtiaz (2023)

Schälli (2012)

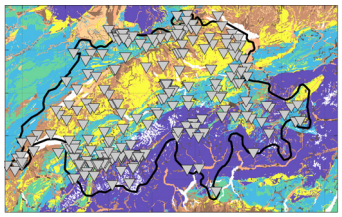
Fiore (2007)



(m)

0 150 >=300

Lithology

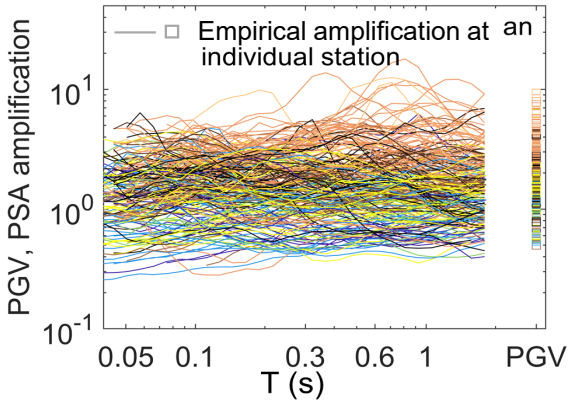


▽ **265** seismic stations

Lithogroups

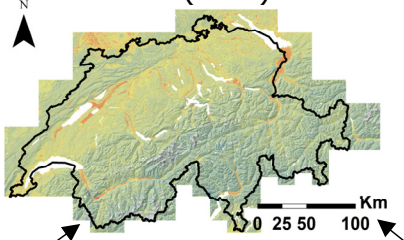
LG1
LG2
LG3
LG4
LG5
LG6
LG7
LG8
LG9

Empirical amplification from seismic stations (2000 – **2024**)

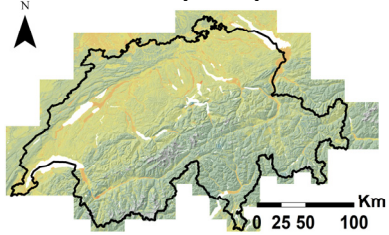



## Regression kriging (RK)

PSA(0.4s)

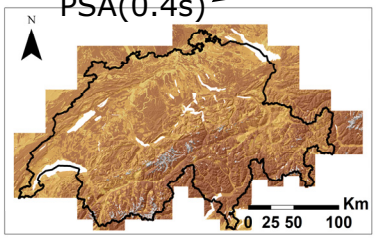



PSA(0.2s)

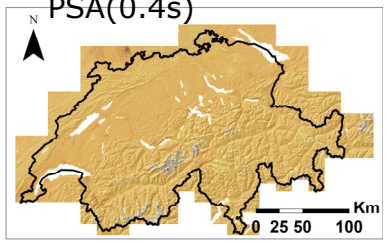



10
3
1
0.3

PSA(0.4s)




PSA(0.4s)




Epistemic uncertainty $\varphi_{S2S}$

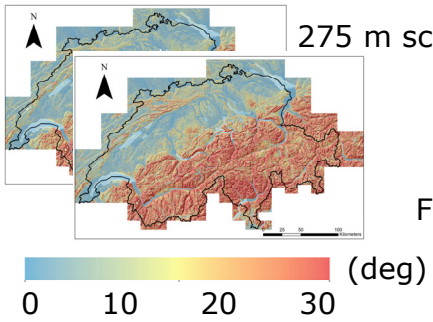
Aleatory variability $\varphi_{SS}$

$\log_{10}$ units

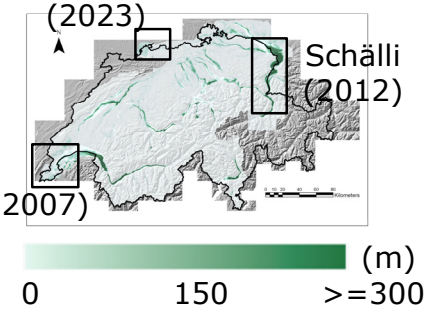
0.05 0.25

# (additional) IERM-CH25 soil amplification maps

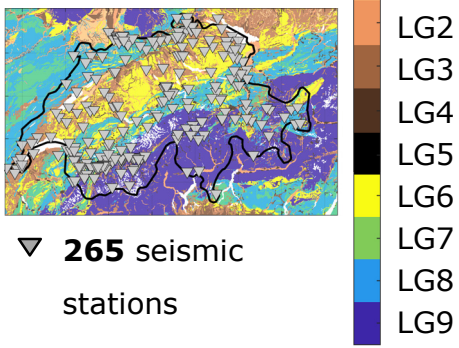
Multi-scale terrain slope



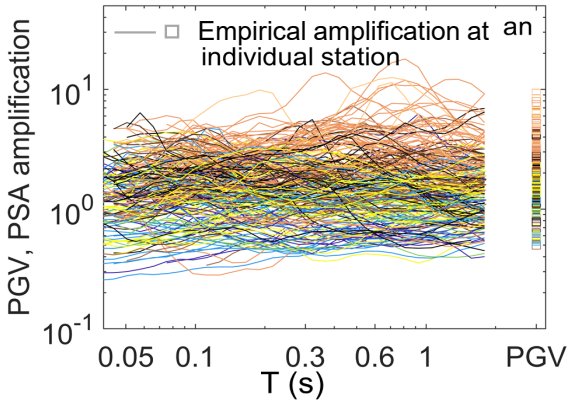

Bedrock-depth model




Lithology

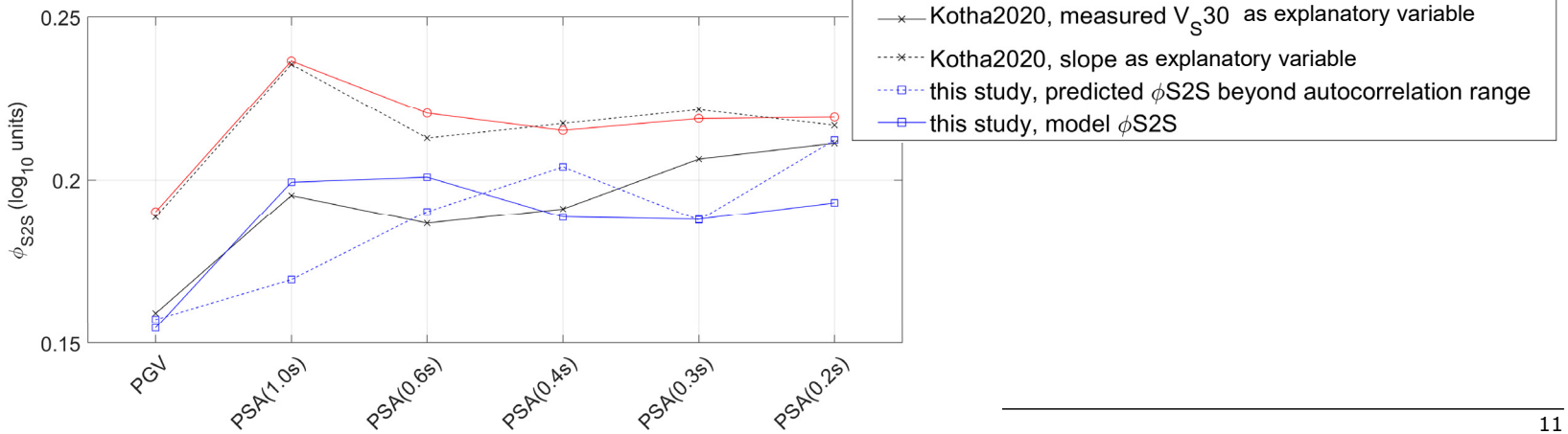



Empirical amplification from seismic stations (2000 – **2024**)



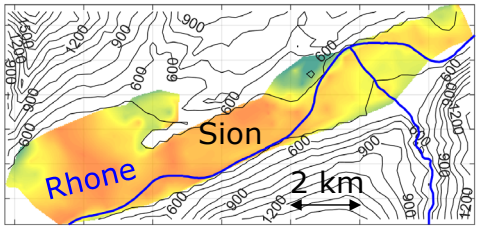

## Regression kriging (RK)

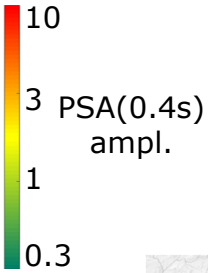
Lower uncertainty!



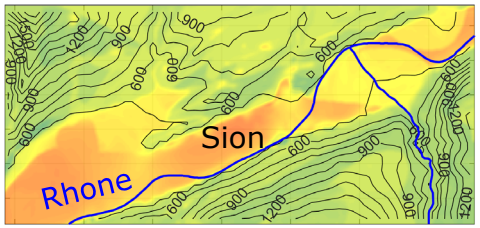
# Testing model performance

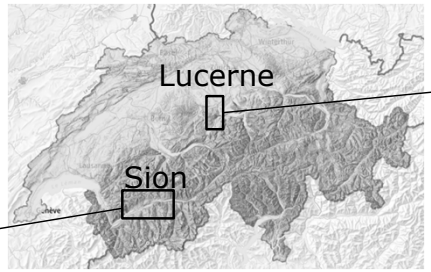
Local amplification model (Perron et al. 2022)



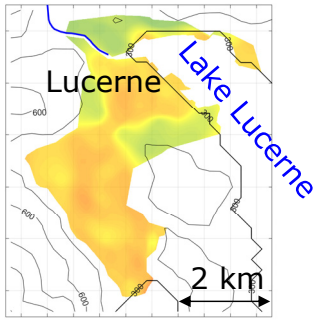




National amplification model (this study)

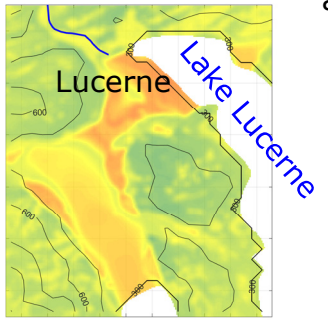


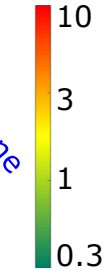




Local amplification model (Janusz et al. 2024)

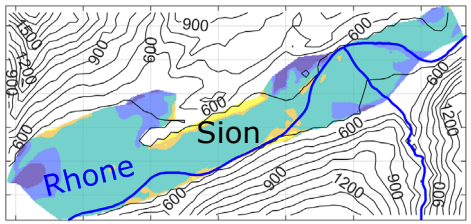


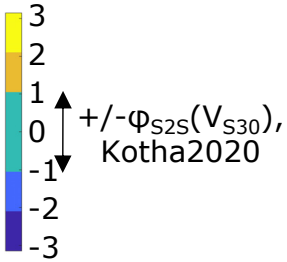

National amplification model (this study)

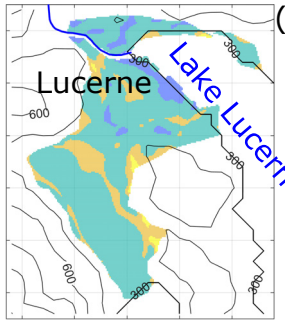


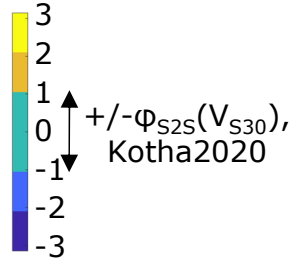

(local-national)/$\varphi_{S2S}$



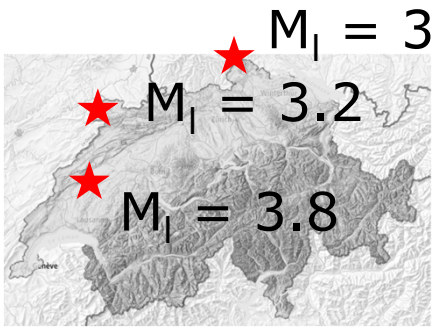



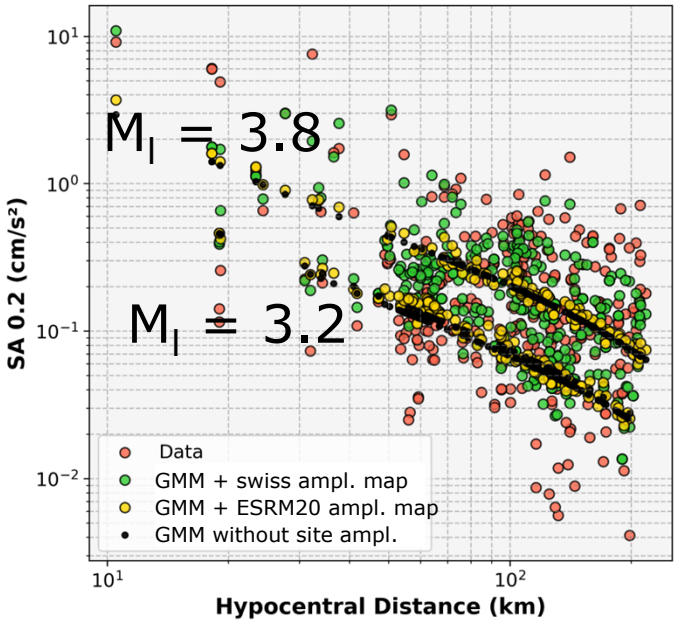

(local-national)/$\varphi_{S2S}$



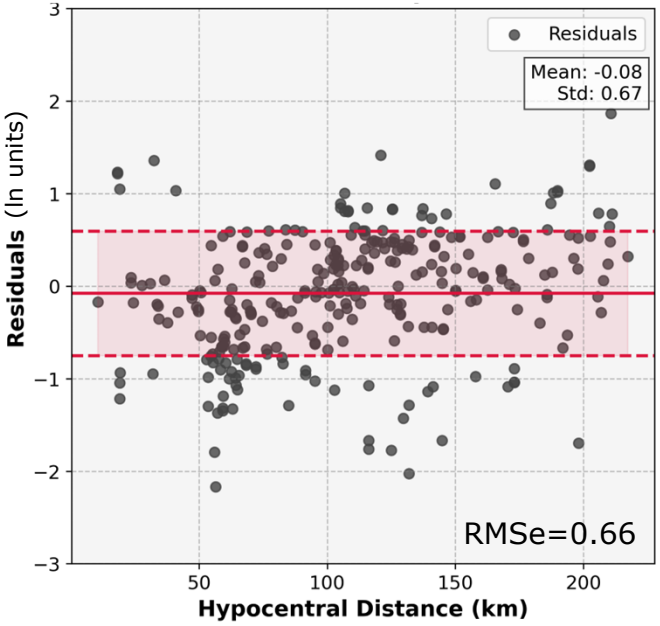
1) Motivation 2) IERM-CH25 risk model 3) Soil response model **4) Testing**

# Testing model performance

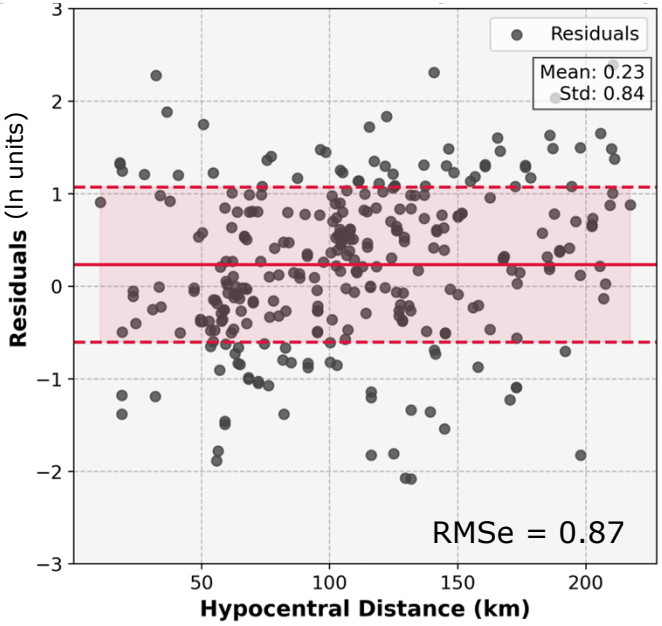



Residuals *vs* distance (site ampl. from this study)




Residuals *vs* distance (site ampl. from ESRM20 model)



# Conclusions

- **Soil amplification is a key component of risk assessment** for (induced) seismicity -> wide range of variability, spatial variations

- **Induced Earthquake Risk Model of Switzerland (IERM-CH25):** extending the Swiss risk model ERM-CH23 to shallow induced seismicity:
  - We verified usability of ERM-CH23 soil amplification for induced seismicity scenarios;
  - We derive PSA(0.4s), PSA(0.2s) amplification maps specifically for IERM-CH25

- Swiss-wide PSA amplification maps (PGV, PSA(1.0 – 0.2s)) derived extrapolating **amplification factors measured at seismic stations** with **site condition proxies**

- PSA amplification maps with **fine spatial resolution (250 m)** and **limited epistemic uncertainty** (φS2S: **comparable** to that enabled by **measured Vs30**)

# Thank you for your attention

paolo.bergamo@sed.ethz.ch

Swiss risk model (ERM-CH23) soil amplification maps available here: https://doi.org/10.3929/ethz-b-000627033

Additional amplification maps for induced seismicity risk model IERM-CH25 available here: https://doi.org/10.3929/ethz-b-000729288

Induced seismicity risk model IERM-CH25 final report: Grigoratos et al., 2025. *Extending ERM-CH23 to shallow induced seismicity in Switzerland*. https://www.research-collection.ethz.ch/handle/20.500.11850/727014

GRID guidelines: Kraft, T., et al. (2025). *Good-Practice Guide for Managing Induced Seismicity in Deep Geothermal Energy Projects in Switzerland.* https://www.research-collection.ethz.ch/handle/20.500.11850/714220

**References**

Bommer JJ, et al. (2022) Ground-motionprediction models for induced earthquakes in the Groningen gas field, the Netherlands. J Seismolog 26(6):1157–1184.

Farajpour Z, Pezeshk S. A ground-motion prediction model for small-to-moderate induced earthquakes for Central and Eastern United States. Earthquake Spectra. 2021;37(1_suppl):1440-1459. doi:10.1177/87552930211016014

Fiore, J., 2007. Quaternary subglacial processes in Switzerland: Geomorphology of the plateau and seismic stratigraphy of western Lake Geneva. Terre et Env. 69

Imtiaz, A., et al.: Developing an urban-scale 3D geophysical model for Basel, Switzerland, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-3505, https://doi.org/10.5194/egusphere-egu23-3505, 2023

Janusz, P., Panzera, F., Bergamo, P. et al. Mapping site amplification with the dense recording of ambient vibration for the city of Lucerne (Switzerland): comparison between two approaches. Bull Earthquake Eng 23, 1431–1462 (2025). https://doi.org/10.1007/s10518-024-02091-9

Kotha, S.R., et al. A regionally-adaptable ground-motion model for shallow crustal earthquakes in Europe. Bull Earthquake Eng 18, 4091–4125 (2020). https://doi.org/10.1007/s10518-020-00869-1

Perron, V. et al.; Site Amplification at High Spatial Resolution from Combined Ambient Noise and Earthquake Recordings in Sion, Switzerland. *Seismological Research Letters* 2022;; 93 (4): 2281–2298. doi: https://doi.org/10.1785/0220210289

Schälli, L., 2012. The diffluence of the Rhine glacier at Sargans in connection to the solid-rock surface model of the Rhine and Seez valley. Master Thesis, University of Zürich, Switzerland.

Suroyo, P.M., et al. (2024). Physically adjusted ground motion prediction equations for induced seismicity at Preston New Road, UK. J Seismol 28, 1147–1171 (2024). https://doi.org/10.1007/s10950-024-10235-2

Swisstopo, Swiss Federal Office of Topography (2019) Felsoberflächenmodell (TopFels25). https://www.swisstopo.admin.ch/en/geodata/geology/models.html

Weatherill, G., et al. (2024). Modelling seismic ground motion and its uncertainty in different tectonic contexts: challenges and application to the 2020 European Seismic Hazard Model (ESHM20). Natural Hazards and Earth System Sciences, 24(5), 1795-1834.

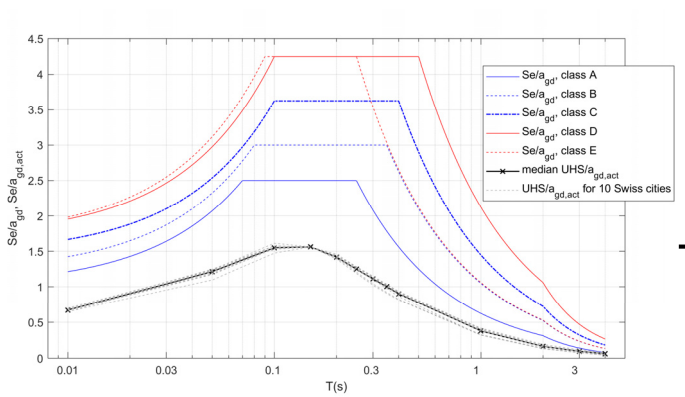
Wiemer S., et al. (2023). Earthquake Risk Model of Switzerland (ERM-CH23). Swiss Seismological Service, ETH Zurich. doi: 10.12686/a20

# 1) Motivation 2) IERM-CH25 risk model 3) Soil response model 4) Testing

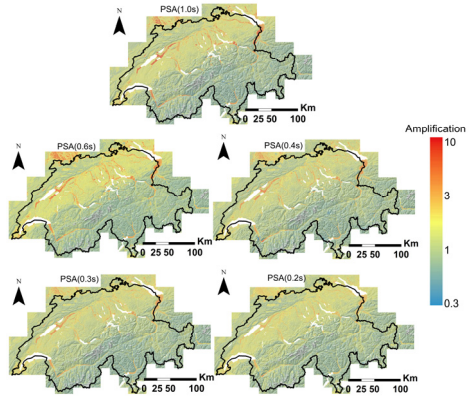
**GRID** guidelines: SED's Good-Practice Guide for managing induced seismicity in deep geothermal projects (Kraft et al. 2025)

| CONCERN ABOUT SECONDARY HAZARDS, EXPOSURE AND VULNERABILITY (within a radius of 5 km) | 0 (little concern) | 1 (medium concern) | 2 (high concern) |
|---|---|---|---|
| Local site amplification (within a radius of 5 km)** | No buildings or infrastructure on soft soils (Ground Class D, E, F in SIA (2003)) | <10% of buildings or infrastructure on soft soils (Ground Class D, E, F in SIA (2003)) | ≥10% of buildings or infrastructure on soft soils (Ground Class D, E, F in SIA (2003)) |
| Exposed population (within a radius of 5 km) | Remote (<100 inhabitants) | Rural (100-20,000 inhabitants) | Urban (>20,000 inhabitants) |
| Industrial or commercial activity (within a radius of 5 km) | Low activity | Medium activity (≥1 enterprise with 100-499 employees or ≥1 industrial installation of a particular value) | High activity (≥5 enterprises with 100-499 employees or >1 enterprise with over 500 employees or ≥2 industrial installation of a particular value) |
| Importance of buildings and infrastructure (within a radius of 5 km) | No buildings or infrastructure of Class II or III, as defined in SIA (2003) | Buildings or infrastructure of Class II (SIA, 2003); no buildings or infrastructures of Class III (SIA, 2003) | Buildings and infrastructure of Class III (SIA, 2003) |
| Infrastructures with considerable environmental risk (within a radius of 5 km) | None | - | One or more |
| Unreinforced cultural heritage (within a radius of 5 km) | <5% buildings listed as important local, regional or national heritage sites | 5-10% buildings listed as important local, regional or national heritage sites | >10% buildings listed as important local, regional or national heritage sites; or any buildings listed as important international heritage sites |
| Susceptibility to secondary hazards (within a radius of 5 km) | Very low | Exists | High |

But there is no complete soil class map for Switzerland




+




Areas with exceedance of C class elastic response spectrum

Consistent mapping of "soft soils" for GRID guidelines