

ISTOS Project Final Conference: Natural Disasters and Safety of Civil Infrastructure

Latest advances in seismic hazard and risk assessment for urban environment and critical infrastructures

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Team work

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Outline

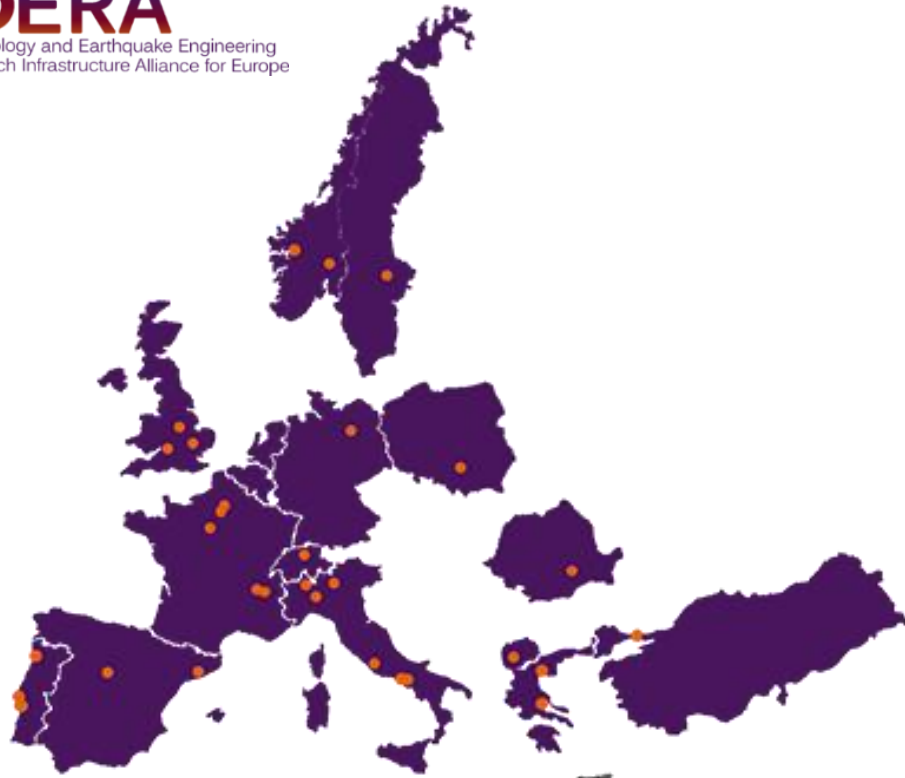
- ❑ The European Seismic Hazard and Risk Models ESHM20 and ESRM20
- ❑ New seismic hazard maps for the EC8 National Annexes of Greece and Cyprus
- ❑ Applications of ESHM20 and ESRM20
 - ❑ Risk assessment at urban environment: Thessaloniki
 - ❑ Critical industrial facilities
- ❑ Vulnerability and seismic risk assessment of critical infrastructures
 - ❑ Early warning and real time risk assessment (SafeSchools)
 - ❑ Risk assessment of schools (RiskSchools)
 - ❑ Systemic seismic analysis of critical infrastructures at urban scale

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<http://www.sera-eu.org/>

SERA
Seismology and Earthquake Engineering
Research Infrastructure Alliance for Europe



The European Seismic Hazard Model ESHM20

- ❑ Update and extension of the 2013 European Seismic Hazard Model ESHM13
- ❑ Robust, transparent, and fully documented seismic hazard model that is scientifically and technically sound, based on the latest datasets and knowledge
- ❑ Uniform seismic hazard model fully harmonized across national borders to cover the Euro-Mediterranean Region
- ❑ Capturing and communicating the data, assumptions, and model uncertainties
- ❑ Input to the 2020 European Seismic Risk Model (ESRM20)
- ❑ **Support the seismic design code revision activities of CEN/TC250 SC8**

Danciu L., Nandan S., Reyes C., Basili R., Weatherill G., Beauval C., Rovida A., Vilanova S., Sesetyan K., Bard P-Y., Cotton F., Wiemer S., Giardini D. (2021) - The 2020 update of the European Seismic Hazard Model: Model Overview. EFEHR Technical Report 001, v1.0.0, <https://doi.org/10.12686/a15>.

Construction of the Unified Earthquake Catalogue

EMEC, the instrumental European-Mediterranean Earthquake Catalogue

S. Lammers, G. Grünthal, G. Weatherill, F. Cotton GFZ Seismic Hazard and Risk Dynamics

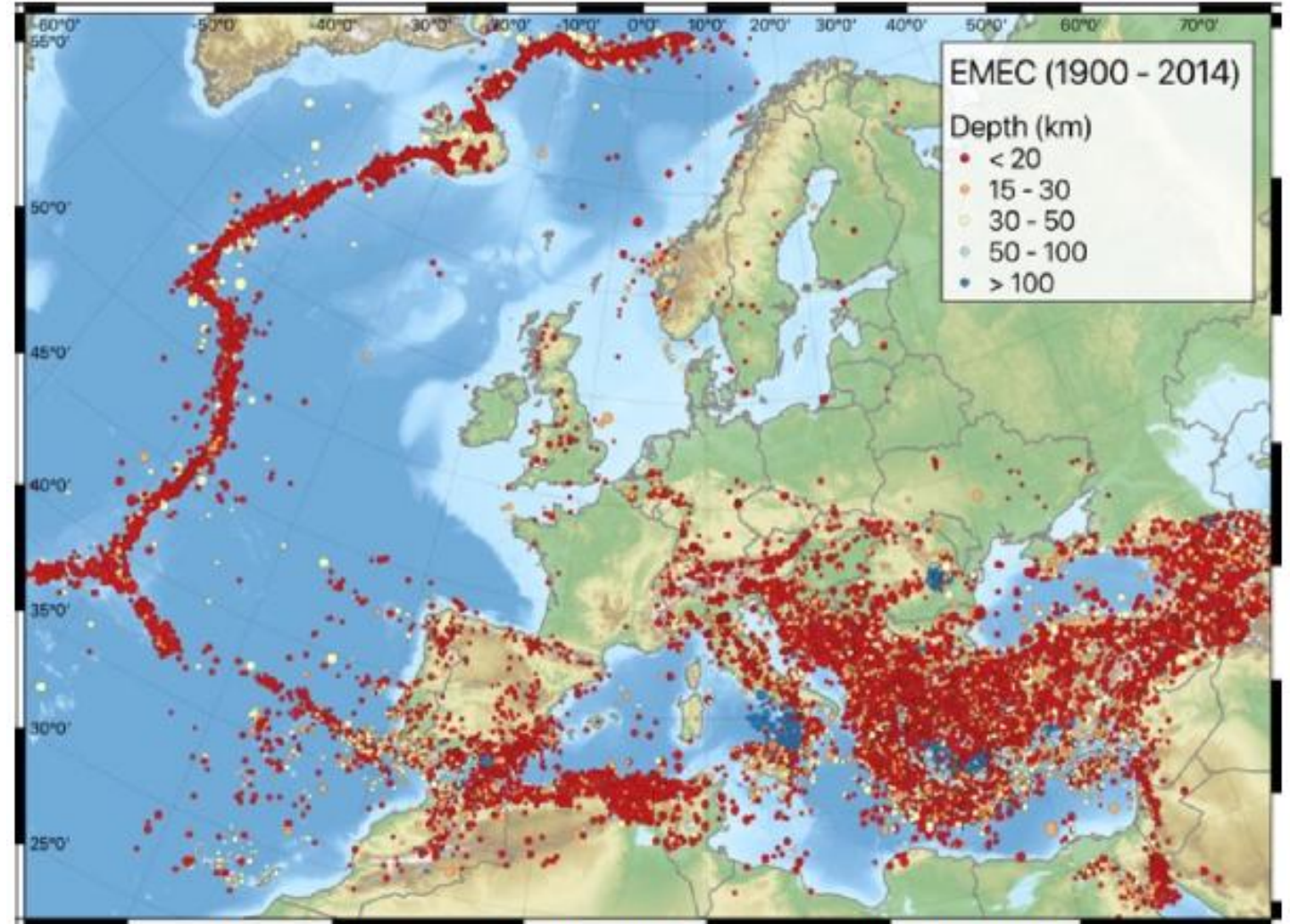


Fig. 1.4 The complete EMEC catalogue for the period 1900 – 2012.

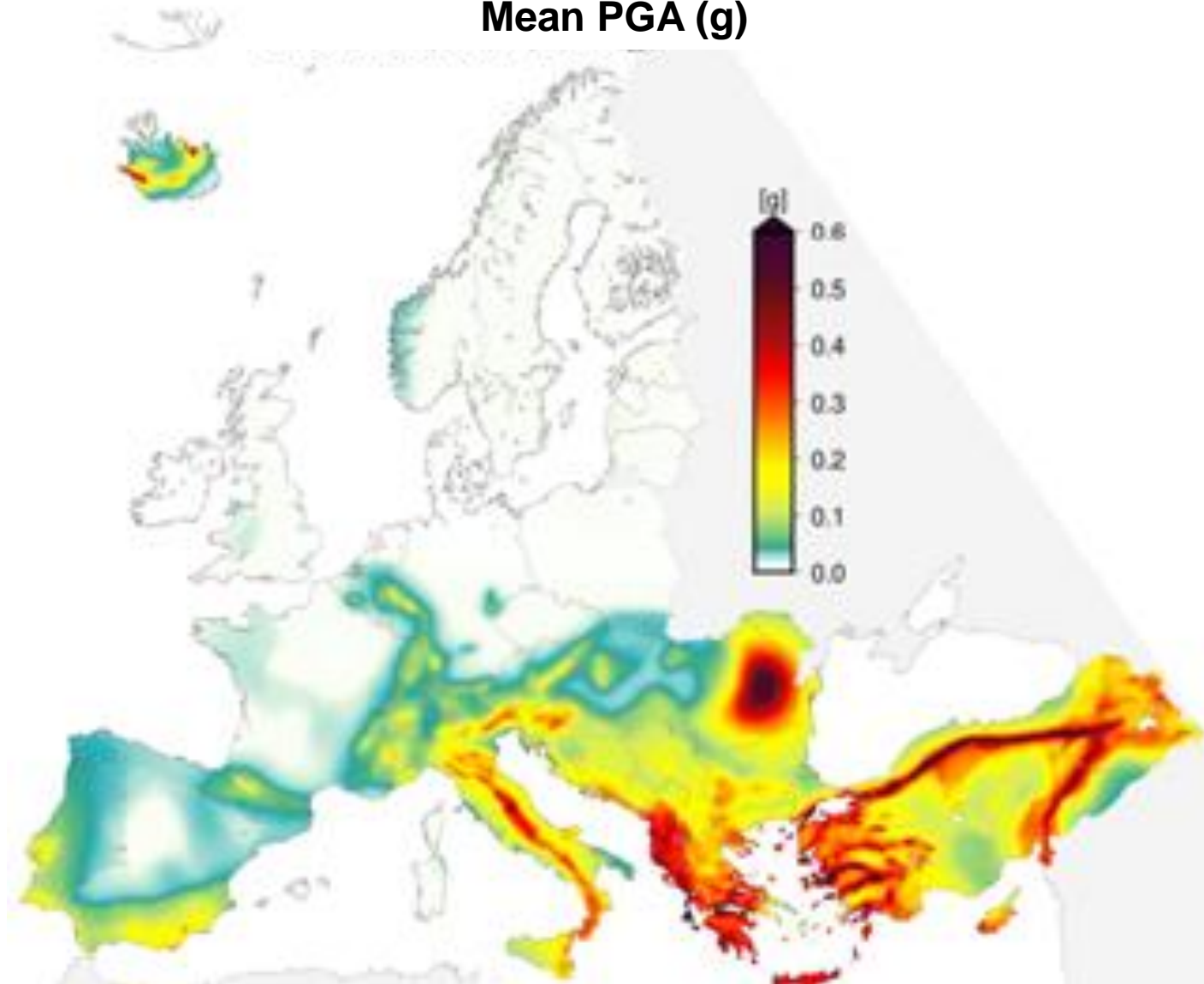
Main results of ESHM20

The ESHM20 results depict time-independent earthquake ground-shaking exceedance levels for a uniform **rock site condition of $V_{s,30} \geq 800$ m/s**.

- 1) More than 500 hazard maps for specified intensity measure types (PGA, spectra acceleration with 5% damping at predominant periods in the range of 0.05s to 5s) and five mean return periods (i.e. 50, 475, 975, 2500 and 5000 years).
 - 2) Hazard curves at every computational site, depicting the mean, median (50th) and four quantiles (5th, 16th, 84th and 95th) for all intensity measure types.
 - 3) Uniform Hazard Spectra depicting the mean, median (50th) and four quantiles (5th, 16th, 84th and 95th) and five mean return periods (i.e. 50, 475, 975, 2500 and 5000 years) estimated at every location of the computational grid.
 - 4) Disaggregation of the hazard results (will be provided as an online tool within the following year).
- All results are available online at hazard.EFEHR.org

Indicative results of ESHM20

Hazard map:
Mean PGA (g)



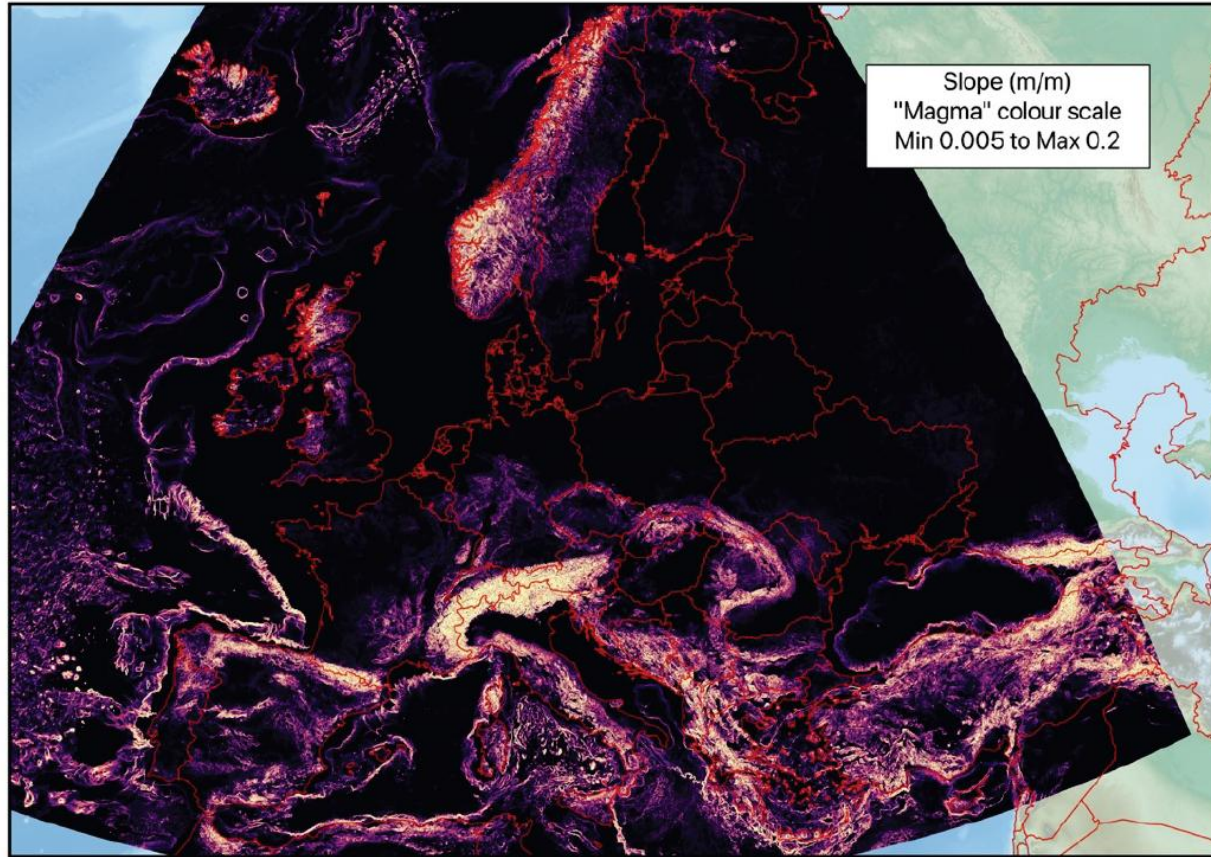
The European Seismic Risk Model ESRM20

Main features:

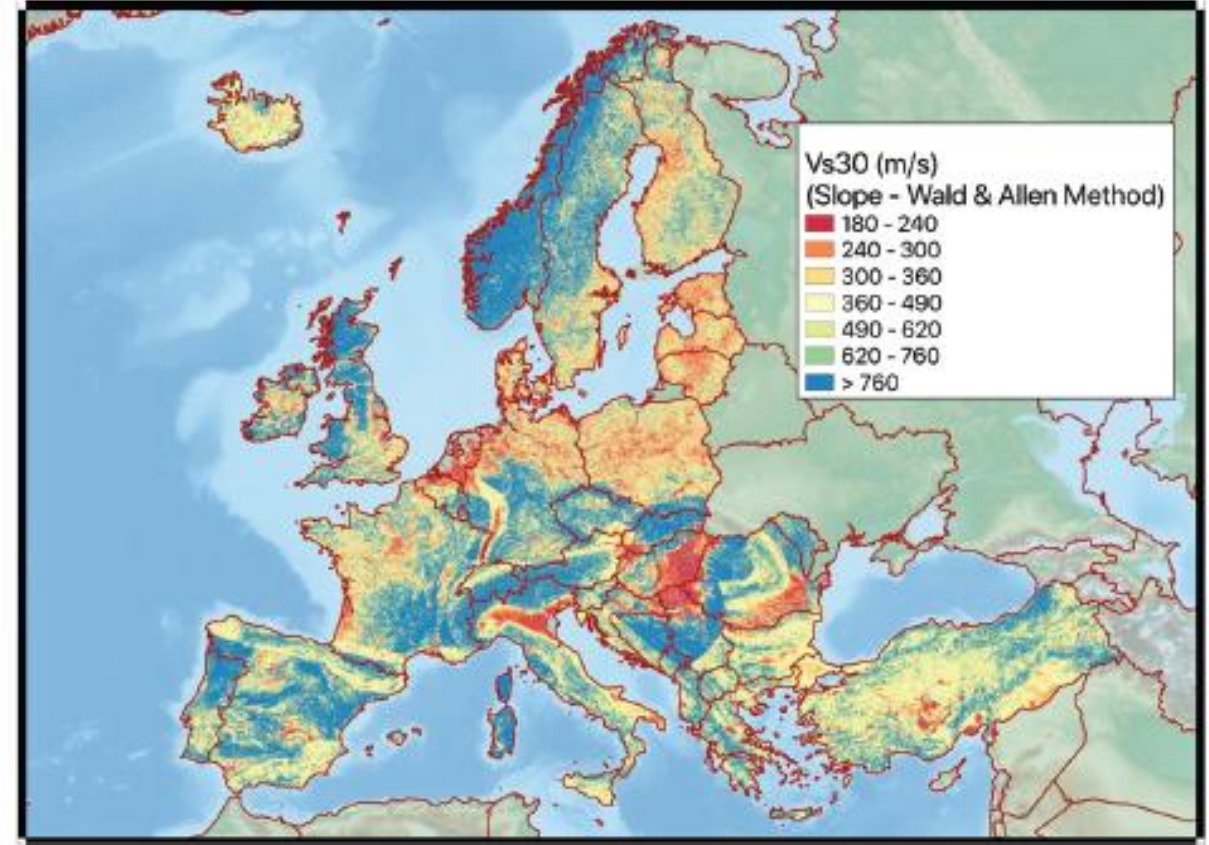
- ❑ **European Seismic Hazard Model 2020 (ESHM20):** Seismogenic source model and ground motion model logic trees
- ❑ **European Site Amplification Model:** European model of proxy site data (geological era and topography) serving as input variables to the ground motion models
- ❑ **European Exposure Model:** distribution of the number, value and occupants of buildings in 44 European countries, divided into residential, commercial and industrial occupancy classes and classified according to different structural classes.
- ❑ **Vulnerability Models:** for a large number of vulnerability classes, a model of the probability of loss (fatality and economic loss) given a level of ground shaking, and a mapping table to map structural classes in exposure model to these vulnerability classes.

Crowley H., Dabbeek J., Despotaki V., Rodrigues D., Martins L., Silva V., Romão, X., Pereira N., Weatherill G. and Danciu L. (2021) European Seismic Risk Model (ESRM20), EFEHR Technical Report 002, V1.0.0, 84 pp, <https://doi.org/10.7414/EUC-EFEHR-TR002-ESRM20>

European Site Amplification Model



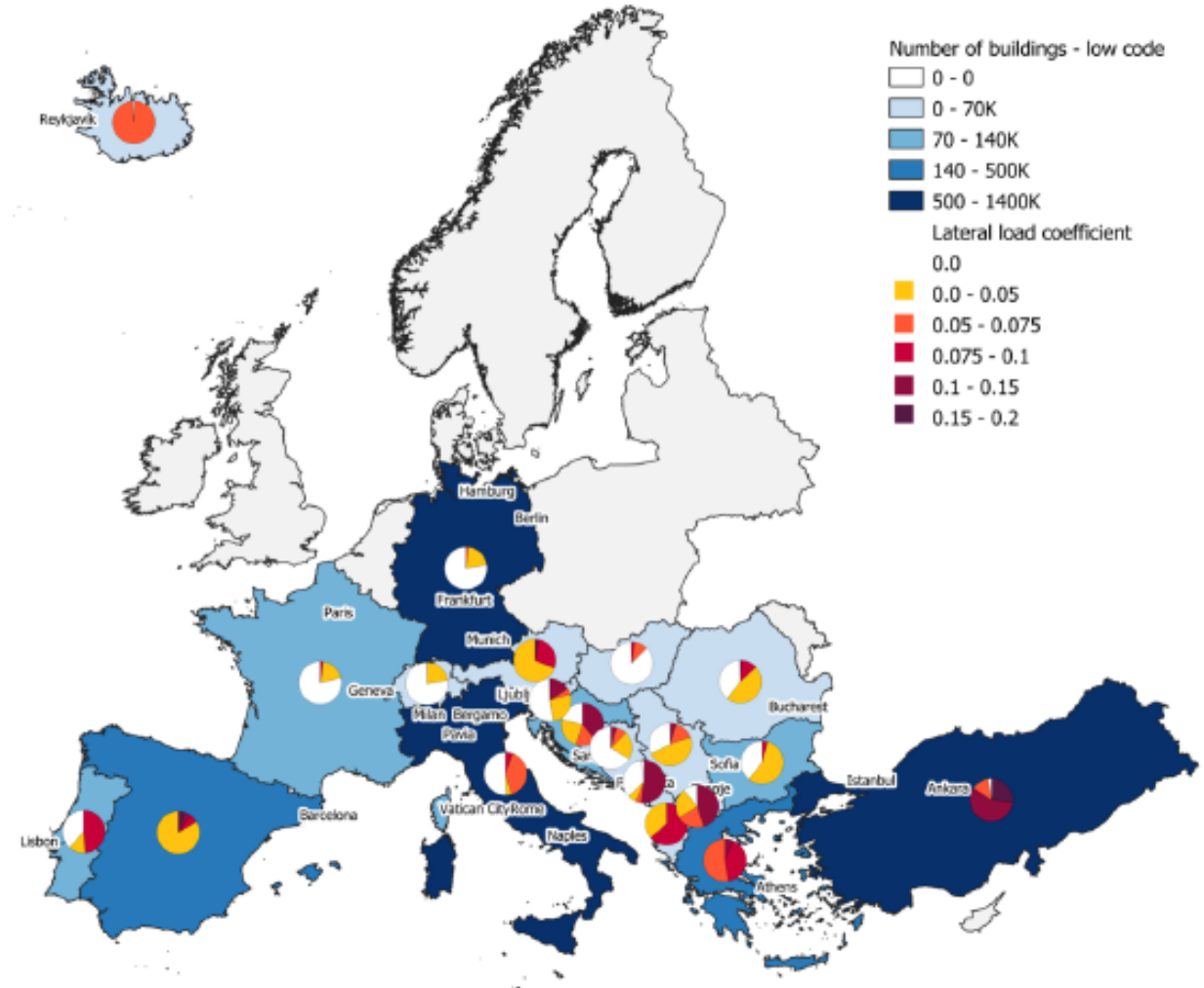
Raster dataset of slope (calculated from the GEBCO_2014 DEM using GMT's grdgradient function)



Vs30 inferred from GEBCO topography/bathymetry using the Wald and Allen (2007) correlation approach

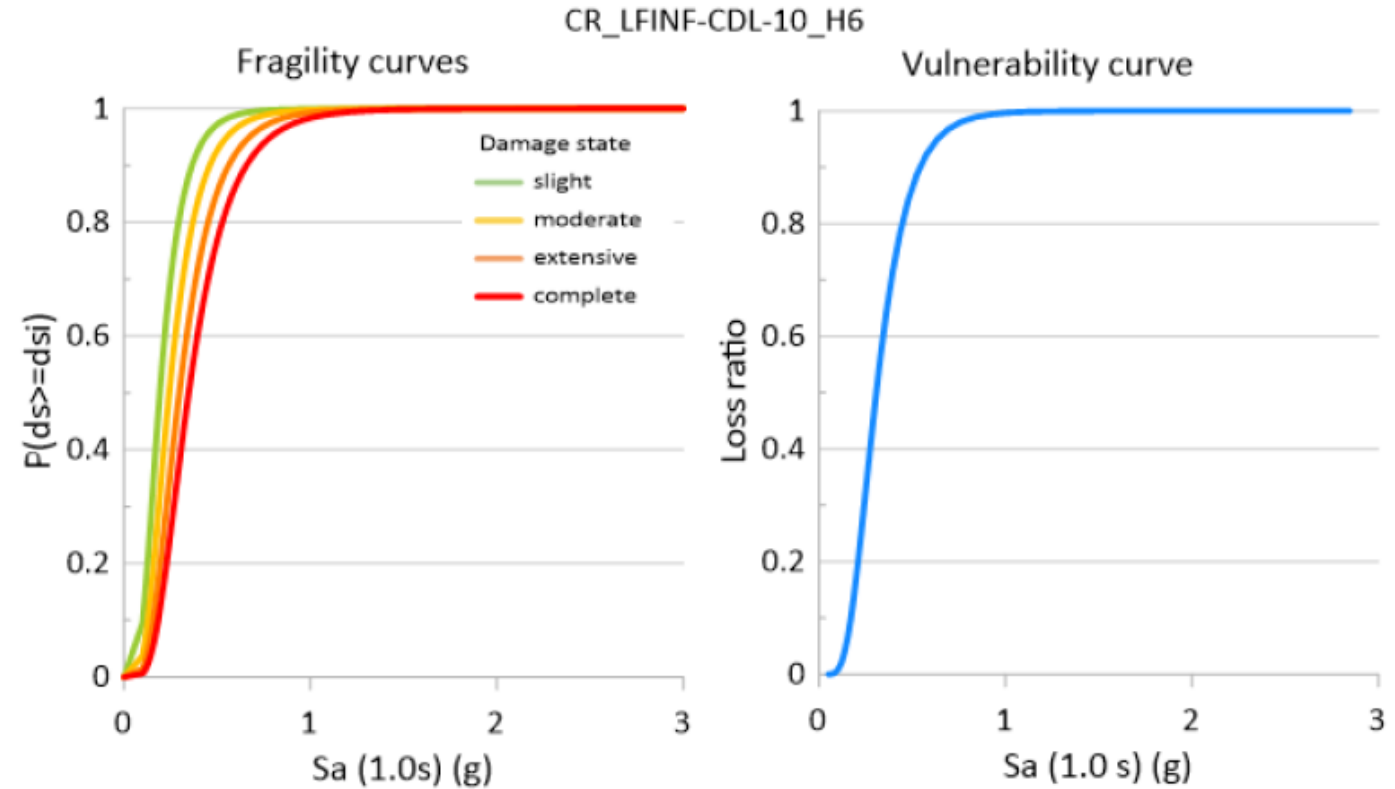
European Exposure Model

- ❑ Exposure models for 44 countries (Europe & Turkey)
- ❑ Residential, commercial and industrial buildings
- ❑ Based mainly on public national census data (at highest resolution available) on dwellings, buildings, population, work force.
- ❑ Source data being shared publicly on EFEHR GitHub repository:
https://gitlab.seismo.ethz.ch/efehr/e_srm20_exposure



European Vulnerability Model

- ❑ Fragility models are produced considering damage state threshold displacements.
- ❑ Vulnerability models for each SDOF are calculated by applying damage-loss models for economic loss and fatalities to the fragility functions.



ESRM20 Indicative Outputs

Average Annual Economic Loss

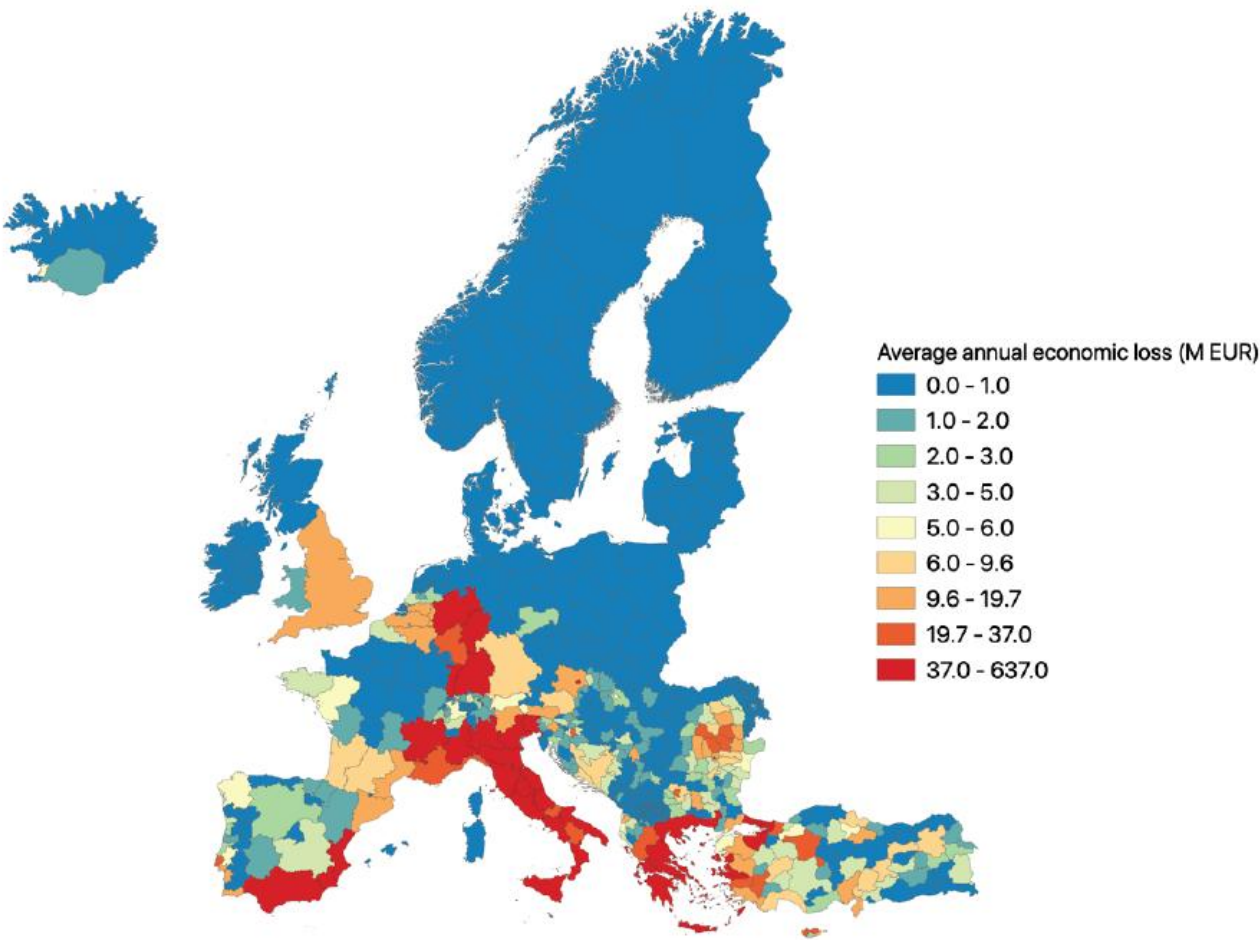


Fig. 6.3 Map of the average annual economic loss across Europe at administrative level 1

Average Annual Loss of Life

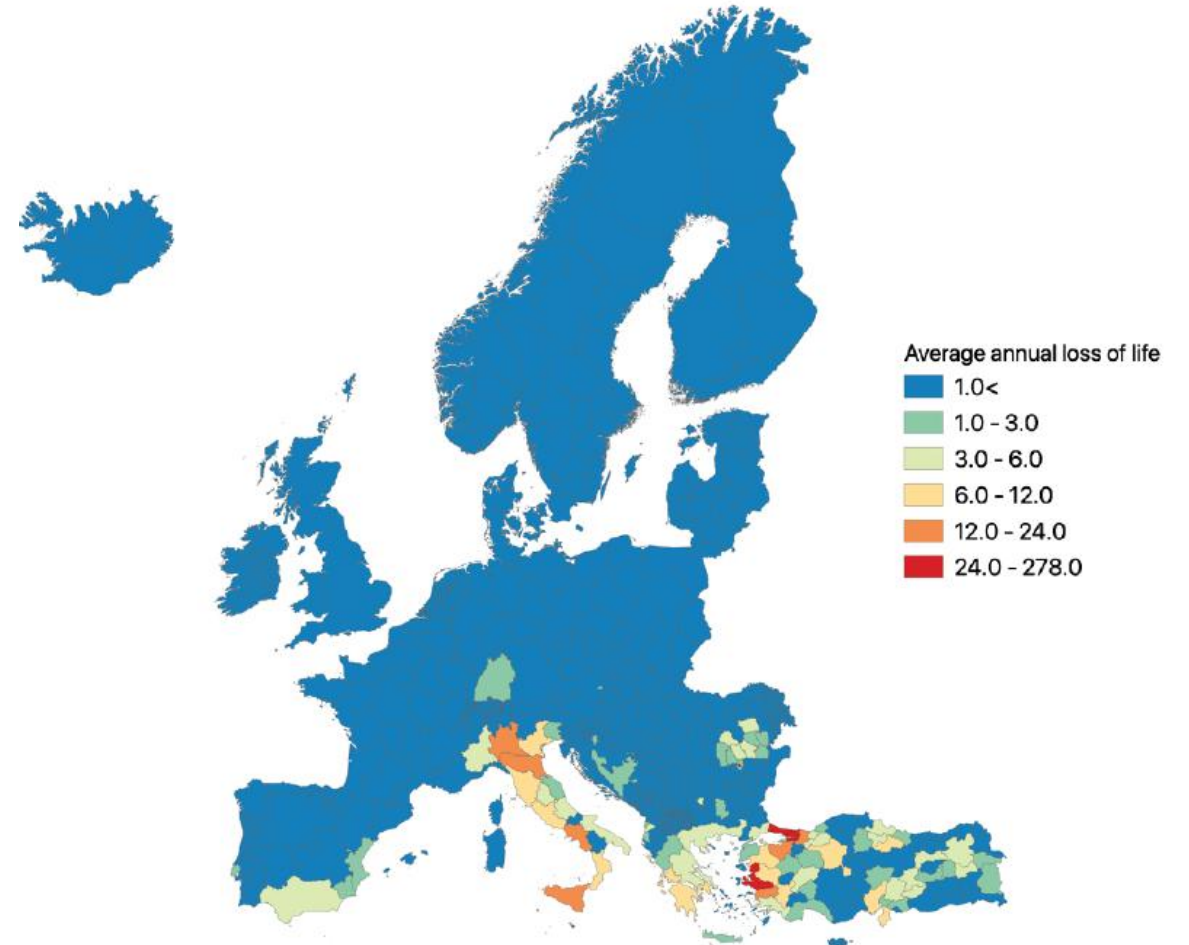


Fig. 6.5 Map of the average annual loss of life across Europe at administrative level 1

Outline

- ☐ The European Seismic Hazard and Risk Models ESHM20 and ESRM20
- ☒ **New seismic hazard maps for the EC8 National Annexes of Greece and Cyprus**
- ☐ Applications of ESHM20 and ESRM20
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New seismic hazard maps for the National Annexes of Greece and Cyprus

- ❑ The seismic hazard maps in Greece and Cyprus have been in force for more than 20 years. They are outdated.
- ❑ The ongoing revision of Eurocode 8 (CEN/TC250/SC8 committee) brings substantial changes in the definition of seismic actions
- **Need and opportunity to revise the National Annexes**
- ❑ The results of the recently published European Seismic Hazard Model ESHM20 (Danciu et al., 2021) an opportunity to update the national seismic hazard maps

Seismic design actions according to the revised EC8

S_α : maximum spectral acceleration (for 5% damping) corresponding to the constant acceleration branch of the horizontal elastic response spectrum

S_β : spectral acceleration (for 5% damping) of the horizontal elastic response spectrum corresponding to an vibration period $T_\beta=1.0s$

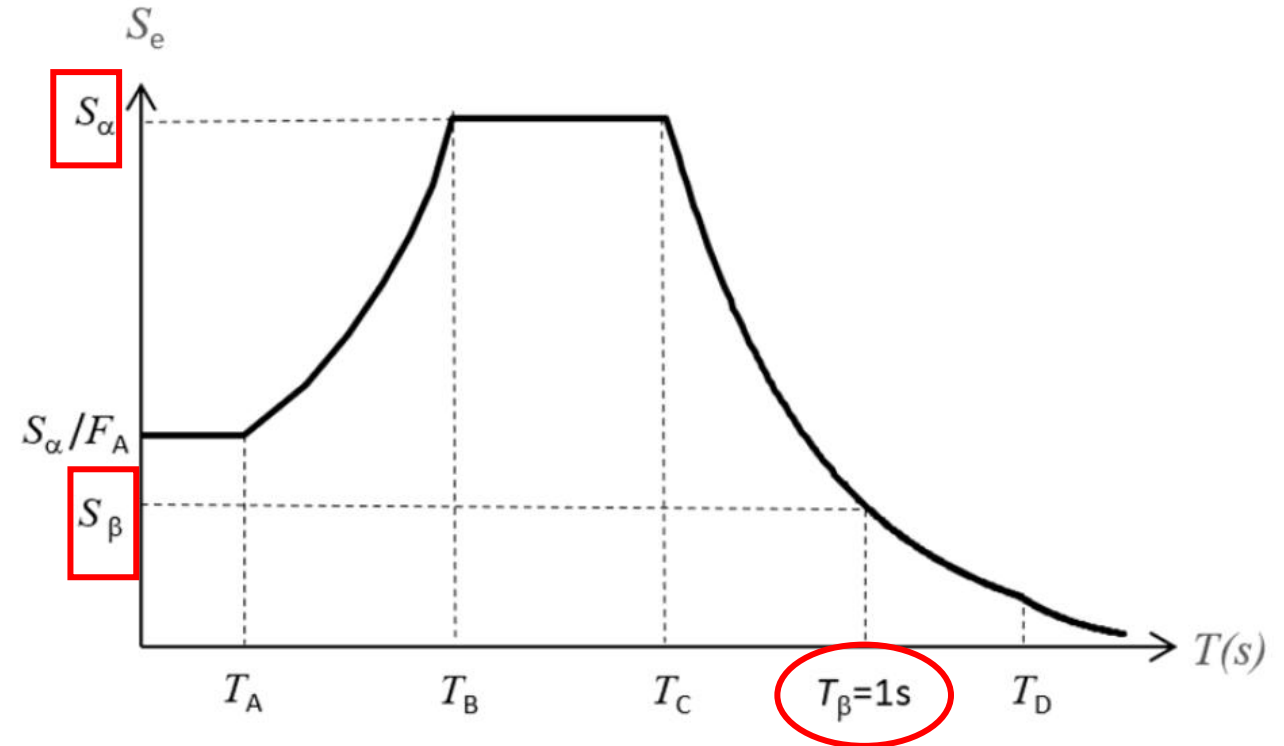
$$S_\alpha = F_T F_a S_{a,475}$$

$$S_\beta = F_T F_\beta S_{\beta,475}$$

F_a : soil amplification factor applied to the S_α

F_β : soil amplification factor applied to the S_β

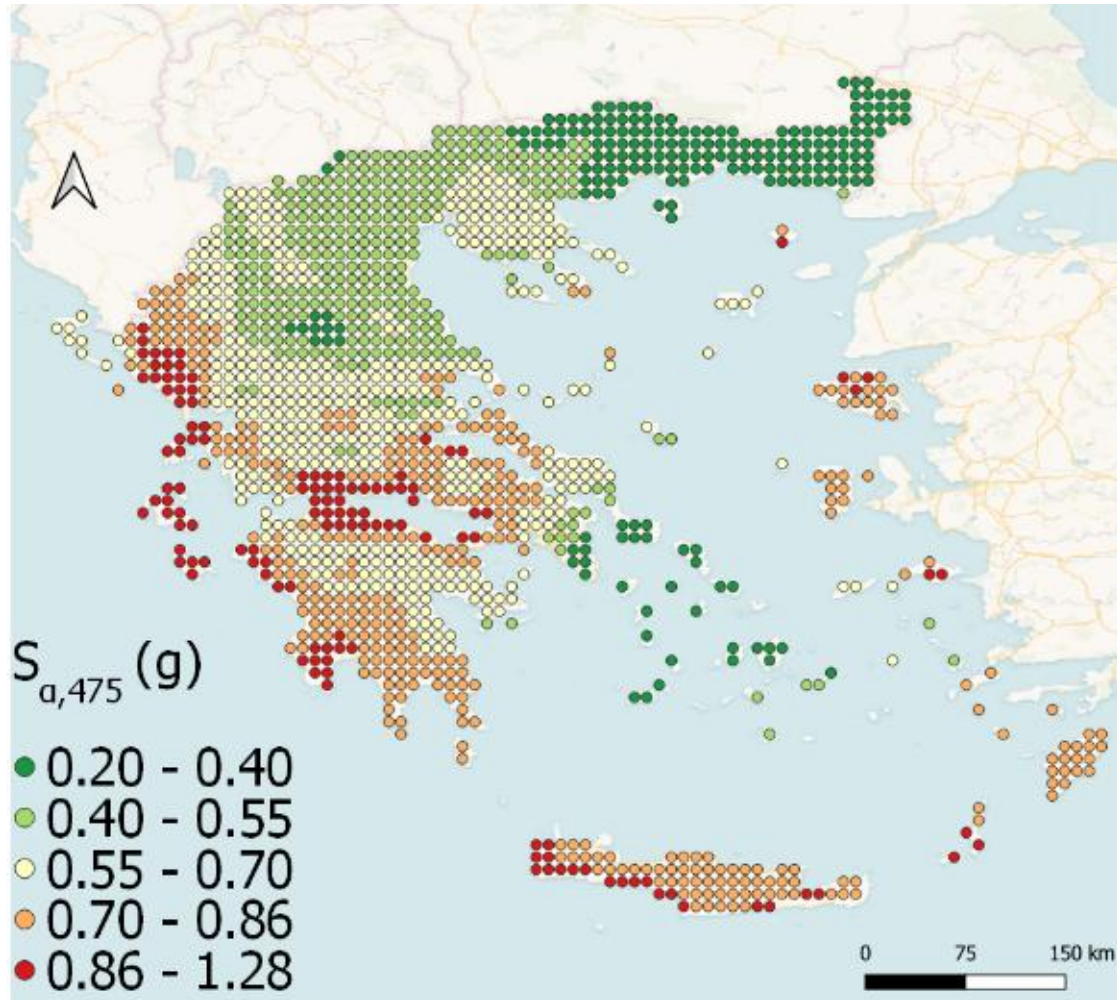
F_T : topography amplification factor



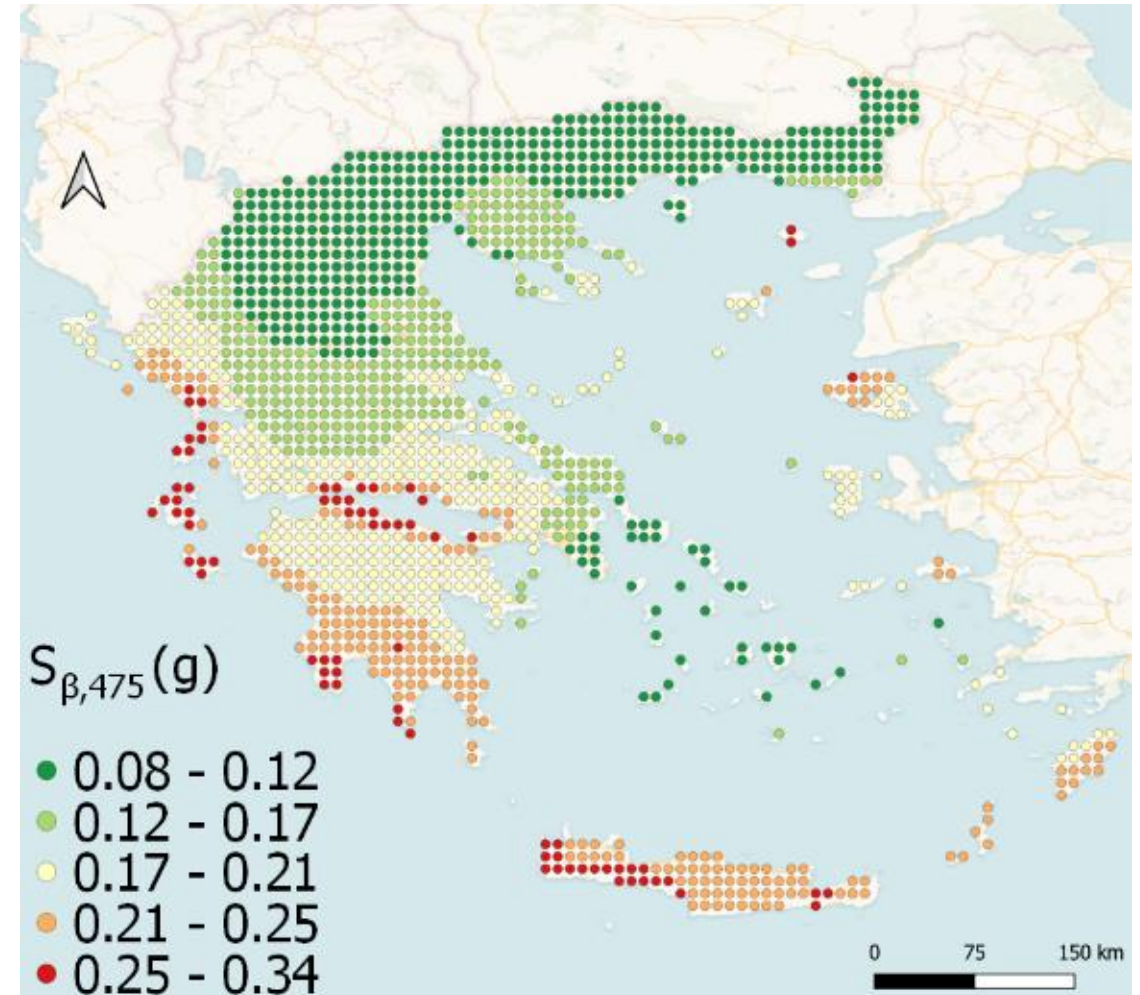
$$T_C = \frac{S_\beta T_\beta}{S_\alpha}$$

ESHM20 $S_{\alpha,475}$ and $S_{\beta,475}$ maps for Greece

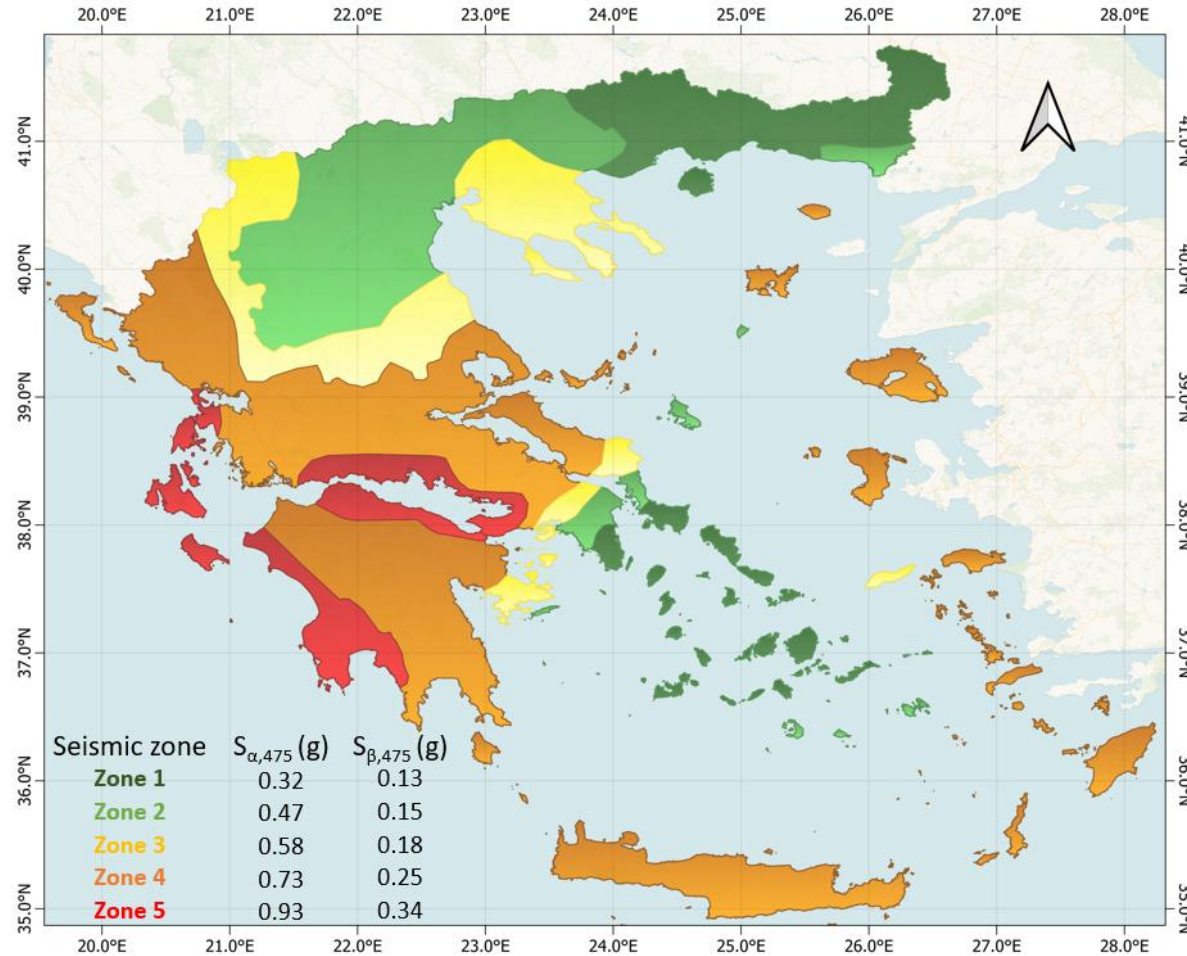
median $S_{\alpha,475}$ (rock)



median $S_{\beta,475}$ (rock)



Seismic hazard map for Greece



Proposed seismic hazard map for rock conditions ($V_s > 800$ m/s)

| Seismic Zone | $S_{\alpha,475}$ (g) | $S_{\beta,475}$ (g) | PGA (g) | T_A (s) | T_B (s) | T_C (s) | T_D (s) |
|--------------|----------------------|---------------------|-------------|-----------|-----------|-----------|-----------|
| Zone 1 | 0.32 | 0.13 | 0.13 | 0.02 | 0.10 | 0.41 | 2.28 |
| Zone 2 | 0.47 | 0.15 | 0.19 | 0.02 | 0.08 | 0.32 | 2.47 |
| Zone 3 | 0.58 | 0.18 | 0.23 | 0.02 | 0.08 | 0.31 | 2.77 |
| Zone 4 | 0.73 | 0.25 | 0.29 | 0.02 | 0.09 | 0.35 | 3.45 |
| Zone 5 | 0.93 | 0.34 | 0.37 | 0.02 | 0.09 | 0.36 | 4.34 |

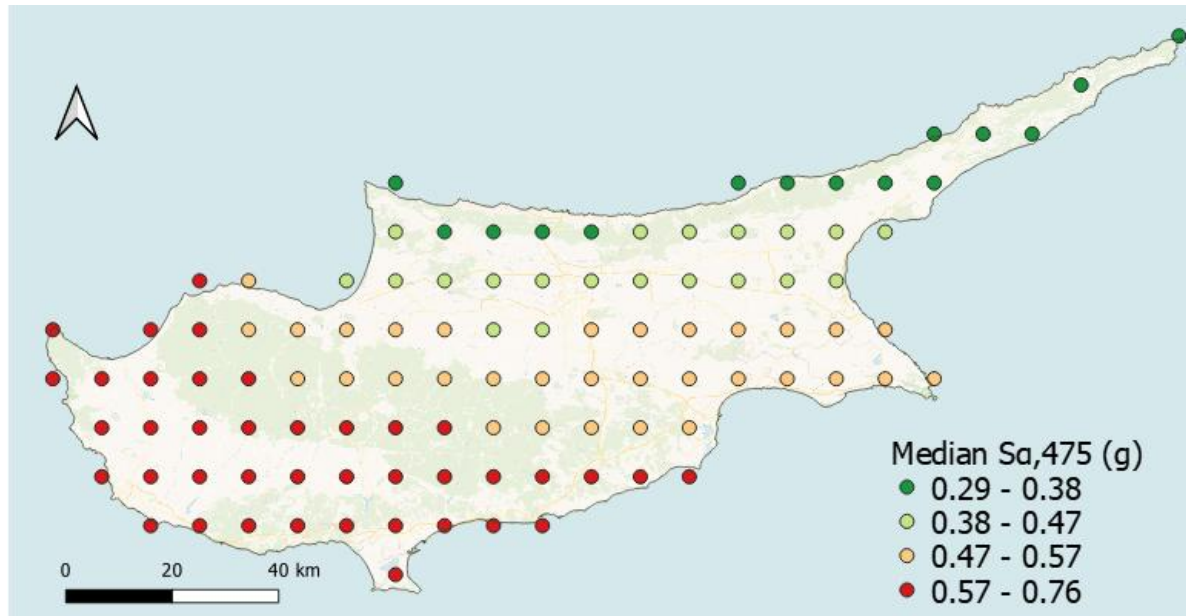
Pitilakis, K., Riga, E., Apostolaki, S. (2023). Seismic hazard zonation map and definition of seismic actions for Greece in the context of the ongoing revision of EC8, Bulletin of Earthquake Engineering (accepted, under revision)

Current seismic hazard map of Cyprus

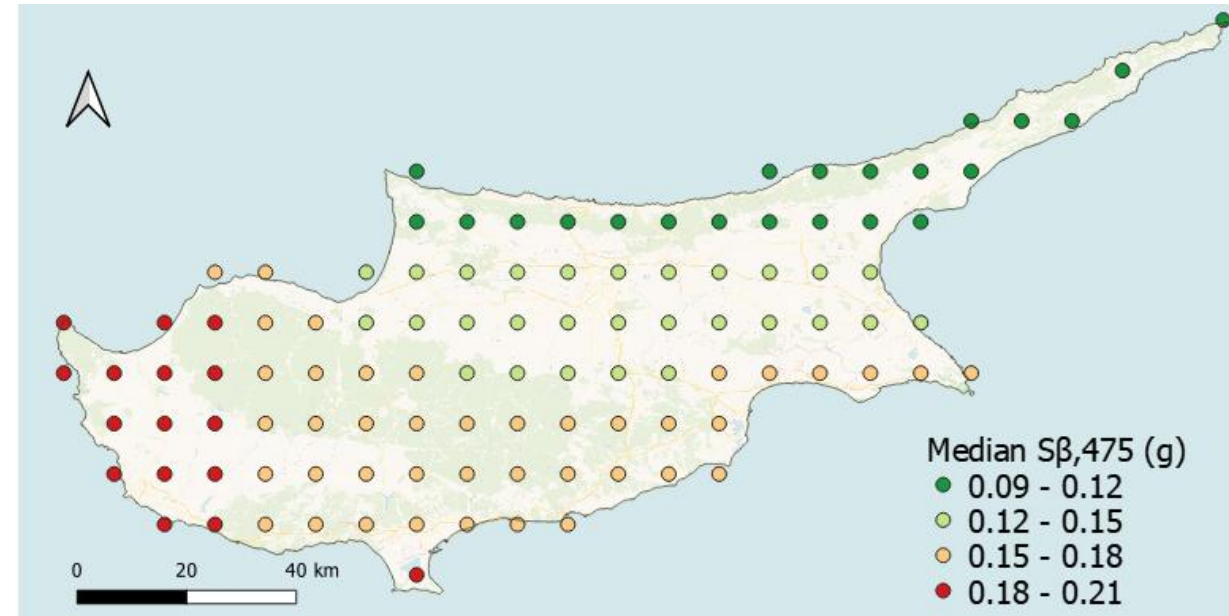


Development of the seismic hazard map for Cyprus

median $S_{\alpha,475}$ (rock)



median $S_{\beta,475}$ (rock)



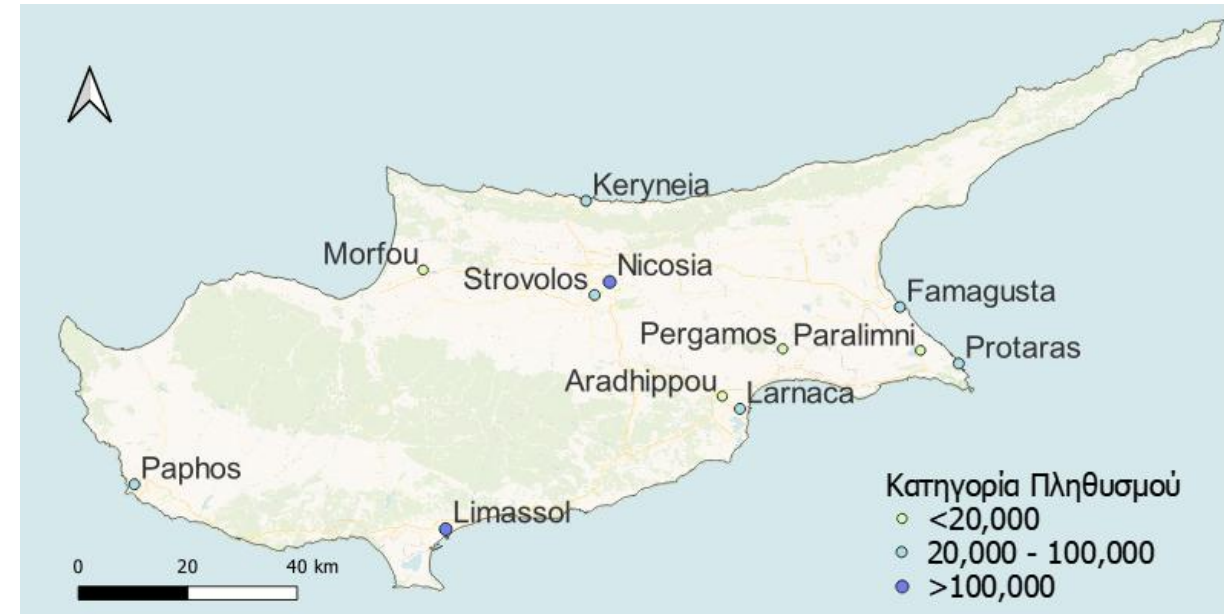
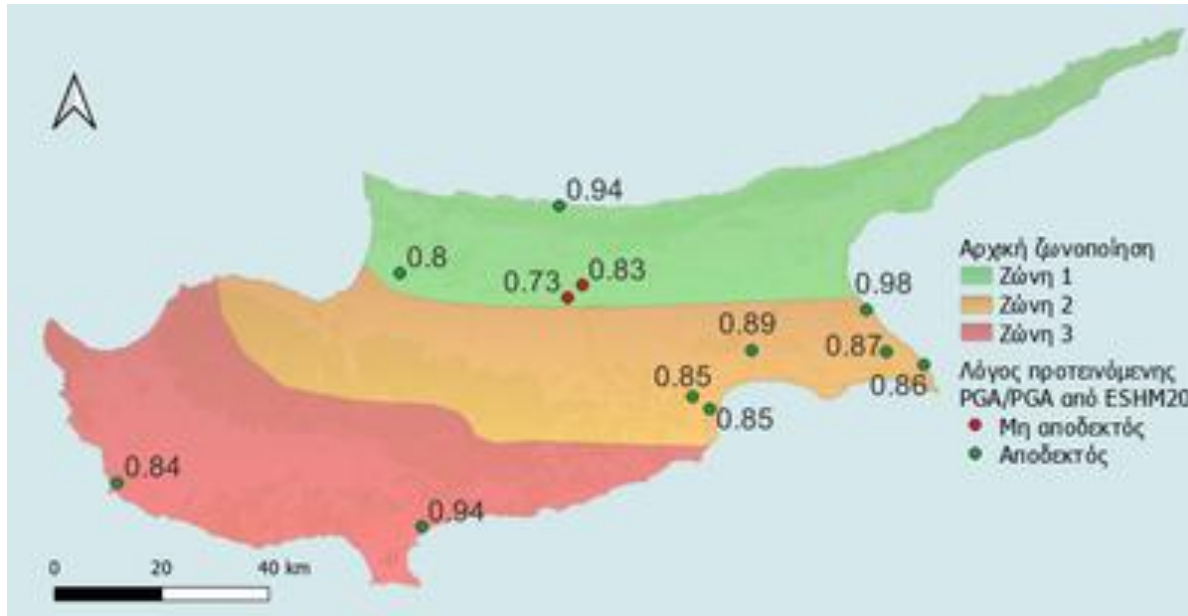
Proposed seismic hazard map for Cyprus

- **Step 1:** Use of the Natural Breaks algorithm (Jenks, 1967) to categorise Cyprus into three zones based on $S_{\alpha,475}$ for rock conditions. The three zones are assigned the mean values of the median values of $S_{\alpha,475}$ and the PGA, defined as $S_{\alpha,475}/2,5$.



Proposed seismic hazard map for Cyprus

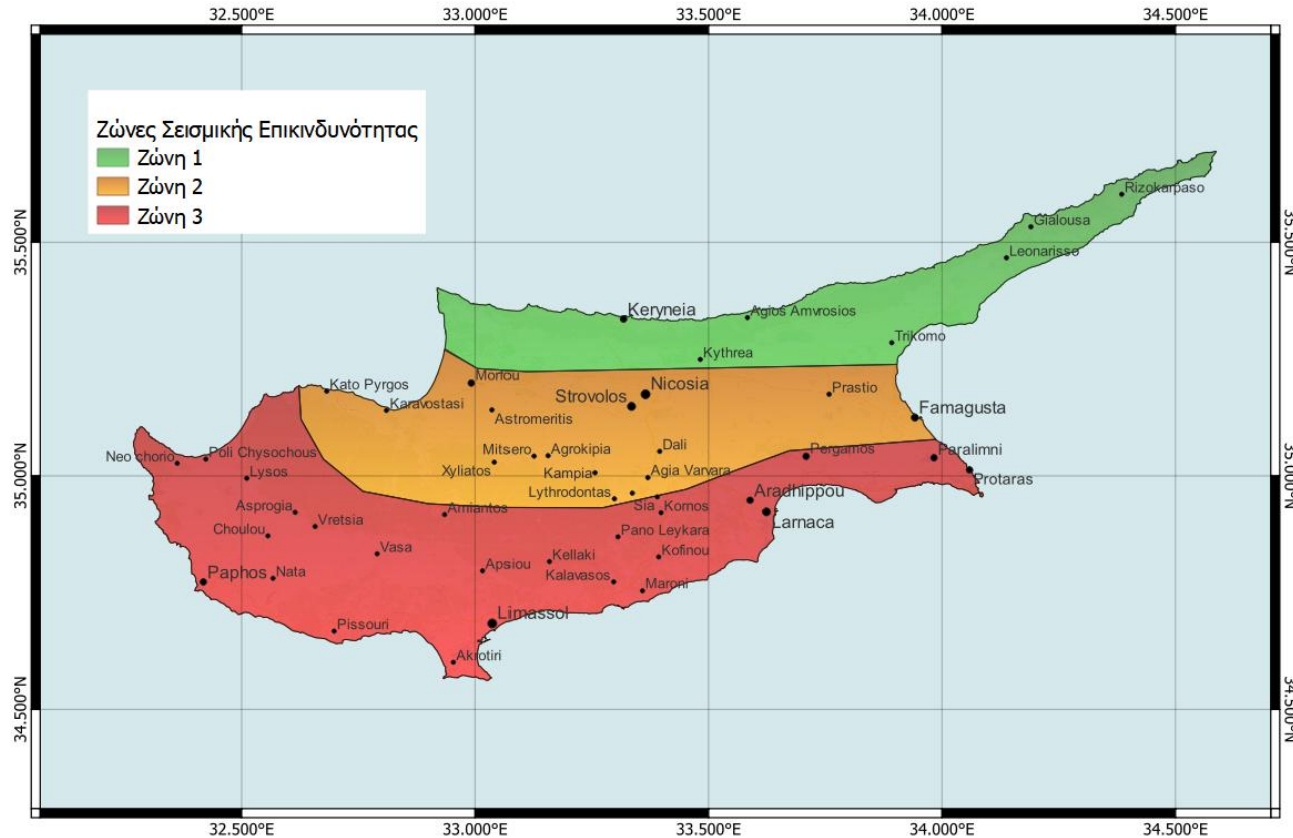
- **Step 2:** Calculation of the ratio of the proposed zone-based PGA to the PGA from the nearest point of the ESHM20 canvas + population criteria



| Population | Accepted range for the ratio Proposed PGA/ PGA from ESHM20 |
|----------------|---|
| <20.000 | ± 0,20 |
| 20.000-100.000 | ± 0,15 |
| >100.000 | ± 0,10 |

Proposed seismic hazard map for Cyprus

- **Step 3:** The procedure is repeated until the population-based criterion is fully satisfied



| Zone | PGA (g) | $S_{a,475}$ (g) | $S_{b,475}$ (g) | T_B (sec) | T_c (sec) | T_D (sec) |
|------|------------|--------------------|--------------------|----------------|----------------|----------------|
| 1 | 0,14 | 0,36 | 0,16 | 0,1 | 0,44 | 2,57 |
| 2 | 0,20 | 0,49 | 0,21 | 0,1 | 0,43 | 3,06 |
| 3 | 0,25 | 0,62 | 0,28 | 0,1 | 0,45 | 3,75 |

Ρήγα, Ε., Κυριακίδης, Ν., Αποστολάκη, Σ., Πιπλάκης, Κ., Πιπλάκης, Δ. (2022). Πρόταση ενός νέου χάρτη σεισμικής επικινδυνότητας για την Κύπρο. 5ο Πανελλήνιο Συνέδριο Αντισεισμικής Μηχανικής και Τεχνικής Σεισμολογίας, Αθήνα, 20-22 Οκτωβρίου 2022

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Probabilistic seismic hazard and risk assessment for Thessaloniki, Greece



- Local site conditions from the microzonation study of Thessaloniki
- Expected ground shaking for the Return Periods (RP) of 101, 475, 975, and 2500 years
- 75,169 residential buildings in Thessaloniki
- Stochastic Event-Based Damage Analysis (SEBD) & Risk Analysis (SEBD) using the Romão et al. (2021) vulnerability model

Apostolaki S, Riga E, Pitilakis D. (2022). Probabilistic seismic hazard and risk assessment of Thessaloniki, Greece. 3rd European Conference on Earthquake Engineering & Seismology. 4-9 September, Bucharest, Romania.



ISTOS

CENTRE FOR NATURAL
HAZARD MANAGEMENT

Results of the PSHA analysis

■ Municipalities

a) RP = 101y

mean PGA (g)

● 0.13 - 0.16

● 0.16 - 0.19

● 0.19 - 0.21

● 0.21 - 0.26

b) RP = 475y

mean PGA (g)

● 0.30 - 0.39

● 0.39 - 0.46

● 0.46 - 0.57

● 0.57 - 0.71

c) RP = 975y

mean PGA (g)

● 0.39 - 0.54

● 0.54 - 0.65

● 0.65 - 0.79

● 0.79 - 0.94

d) RP = 2500y

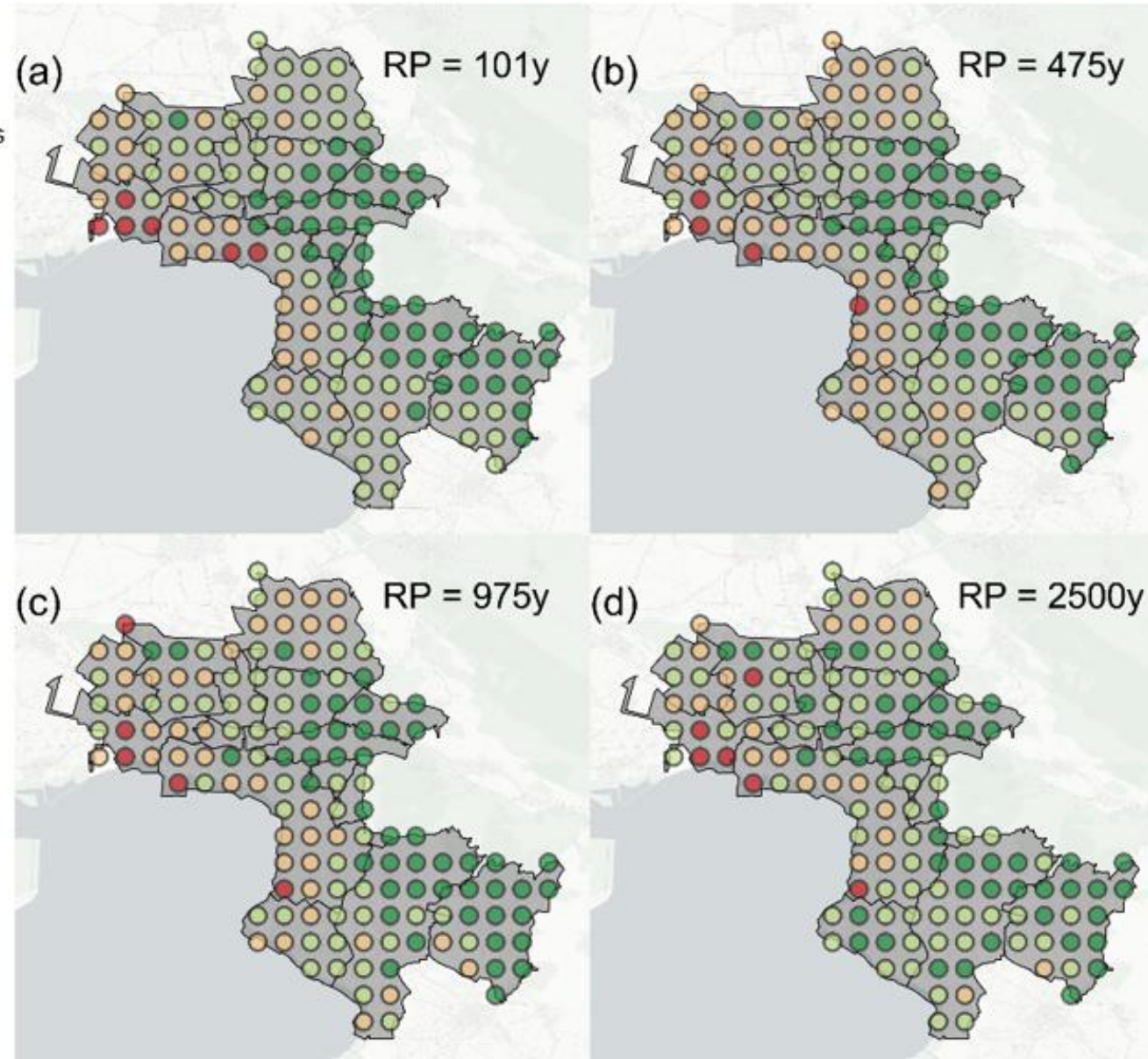
mean PGA (g)

● 0.53 - 0.80

● 0.80 - 1.01

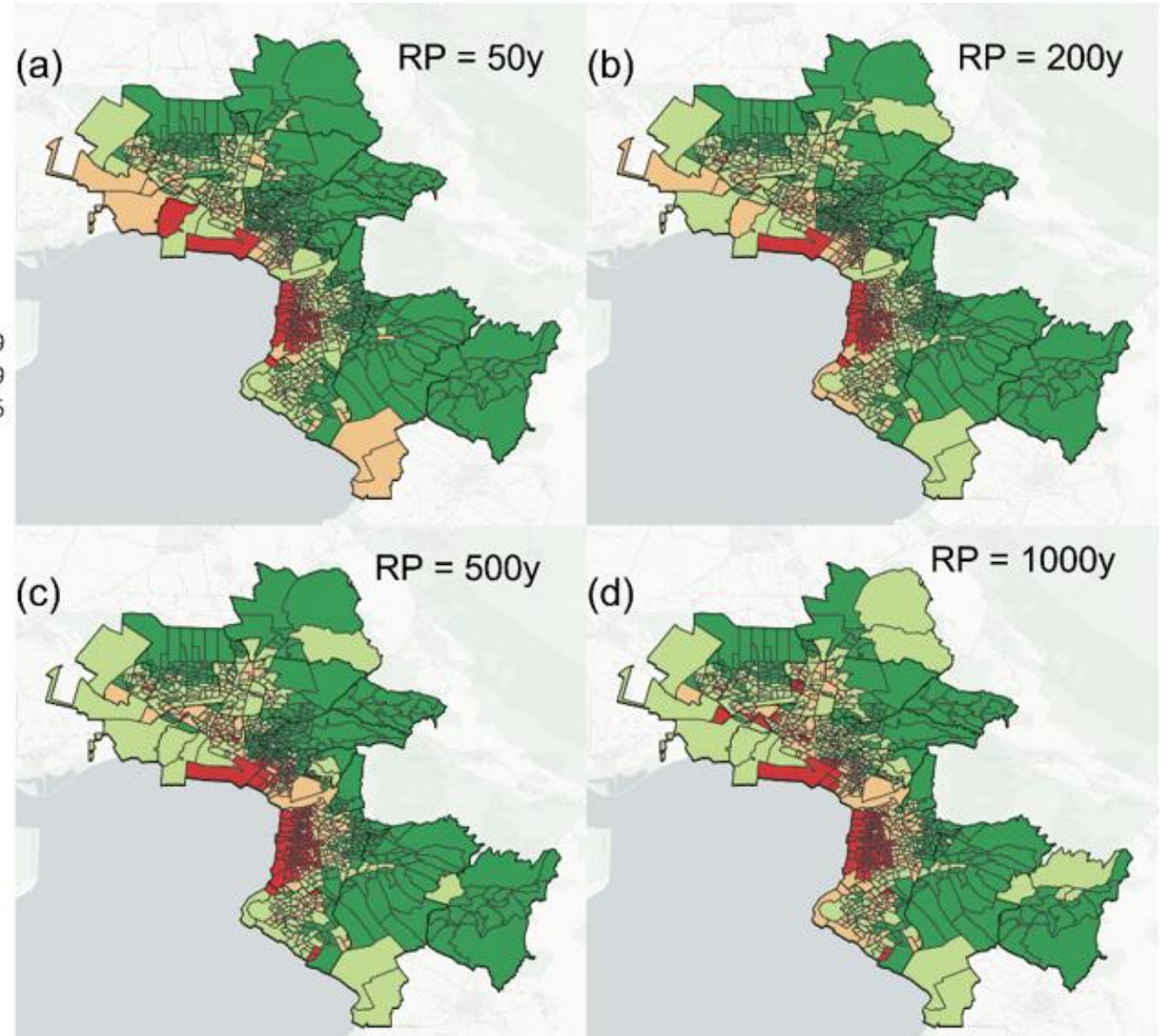
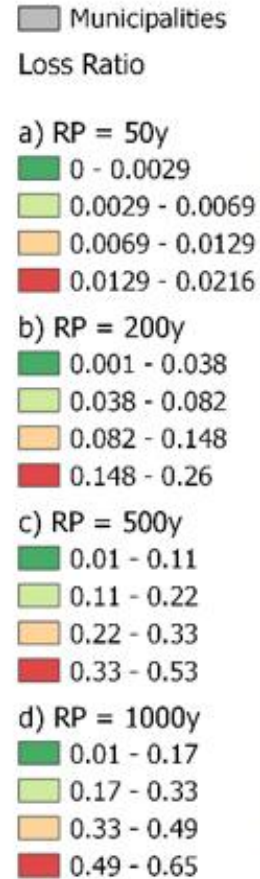
● 1.01 - 1.34

● 1.34 - 2.00



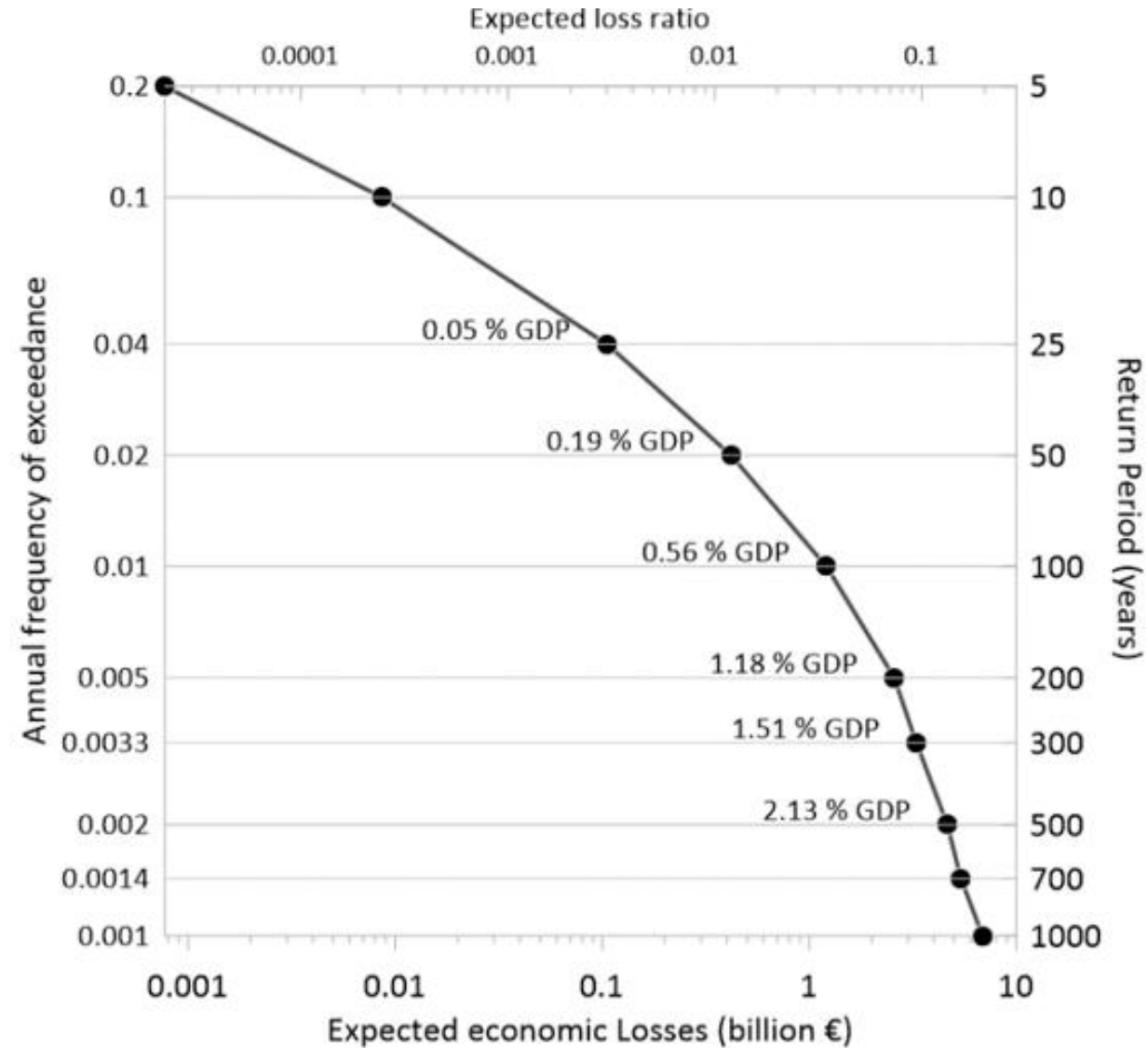
Results of the Stochastic Event-based Risk analysis

$$\text{Loss ratio} = \frac{\text{Repair cost}}{\text{Replacement cost}}$$



Loss exceedance curve for Thessaloniki

GDP = 217.7 billion €



Risk assessment at national level (Greece)

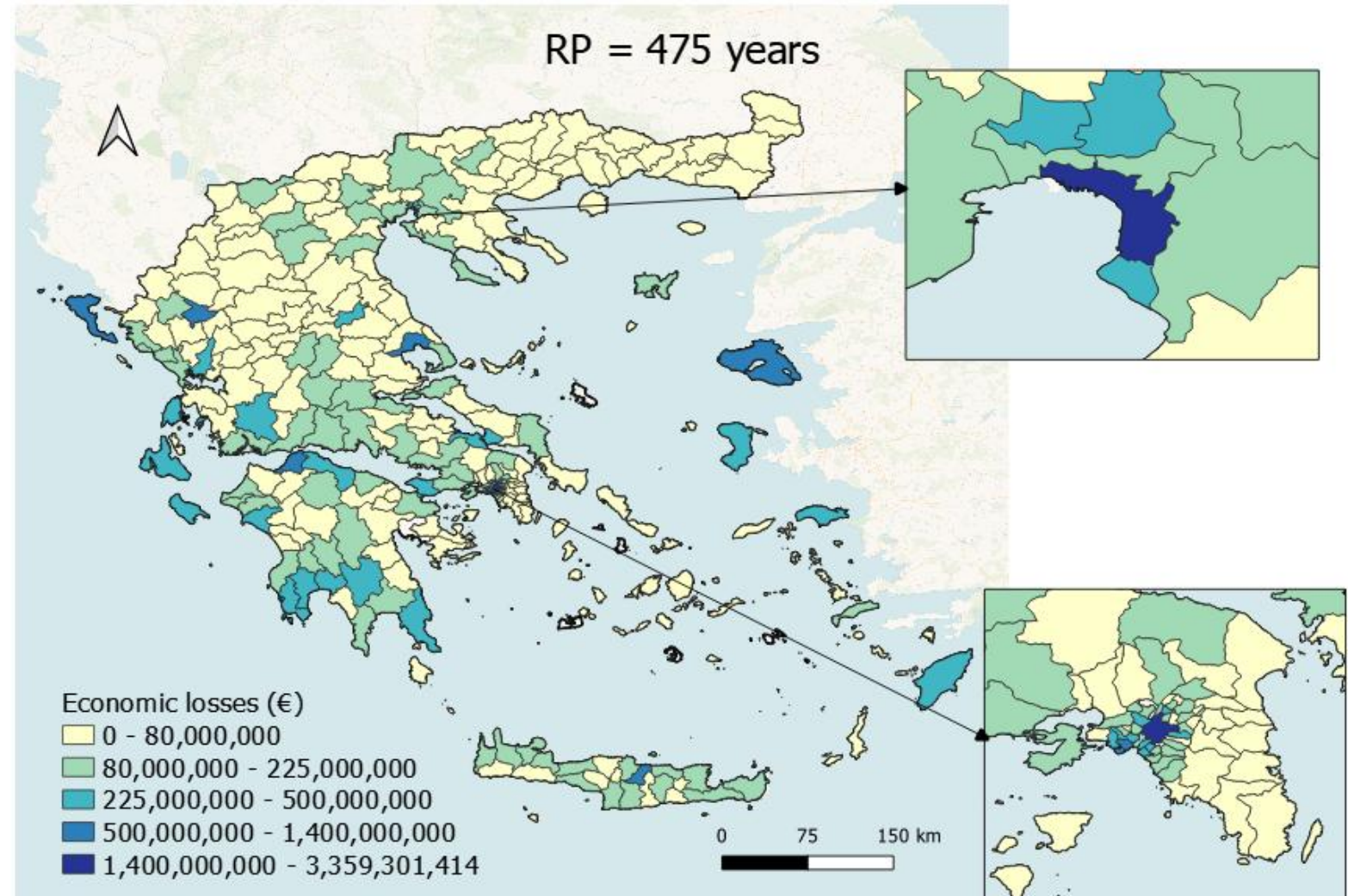
Economic losses under exposure to 475y-return period ground motion

Total losses:
39,3 billion €

Loss ratio= 0.09

Residential buildings
2011 census

Total reconstruction cost:
450 billion €



Seismic risk assessment of the Cyprus building stock

Critical buildings and facilities

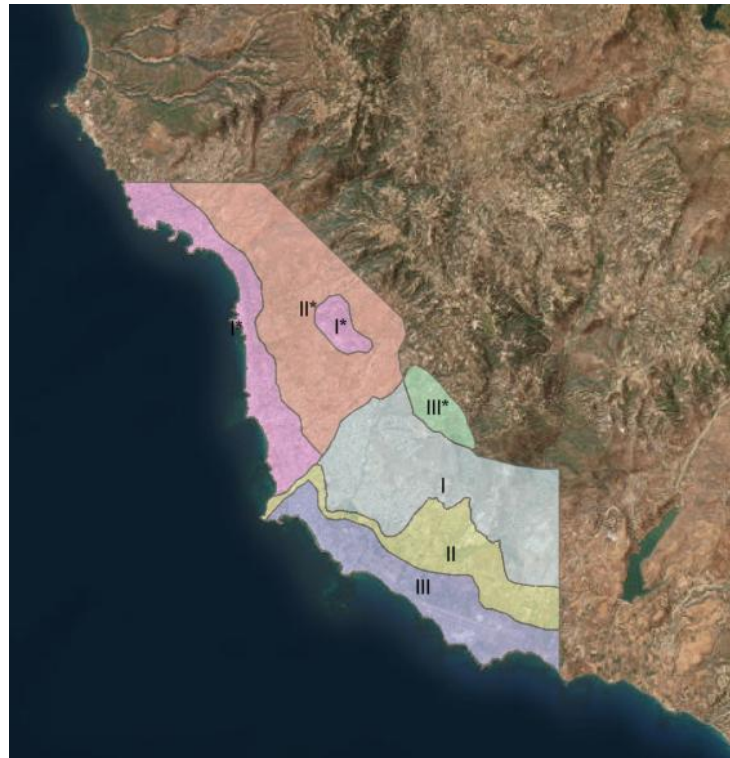
Existence of detailed microzonation studies covering all major cities allows the accurate evaluation of site specific ground amplification

Microzonation studies in Cyprus

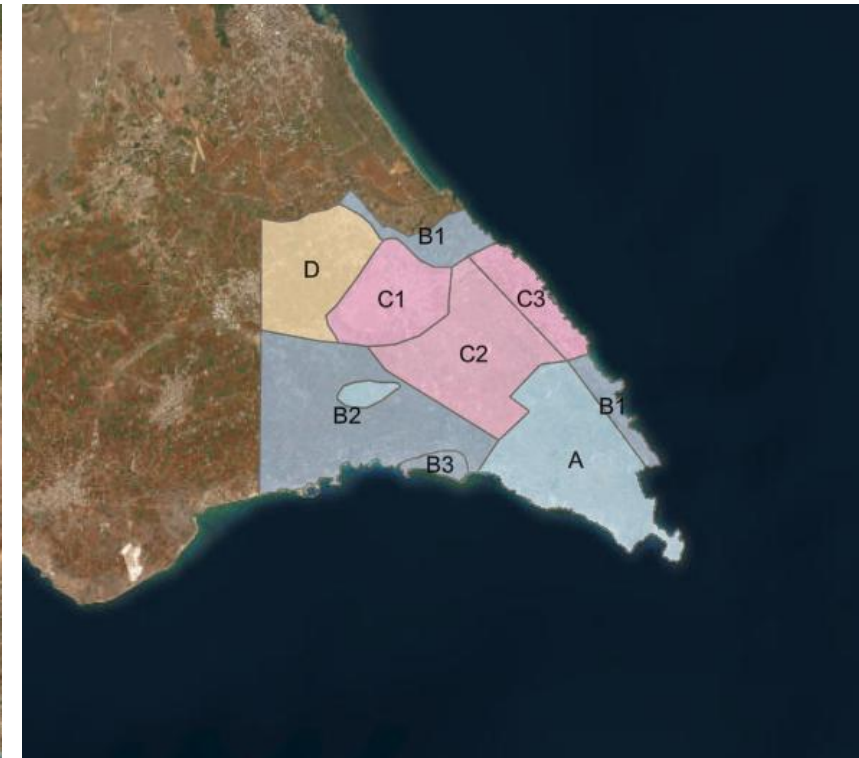
Limassol (2000)



Paphos (2005)



Ammochostos (2020)



Current EC8 – Part 4

- ❑ partially covers the design of industrial facilities (silos, tanks and pipelines)
- ❑ provides recommended values for importance factors, γ_i , for four importance classes I-IV

| Important Class | Importance factor γ_i |
|-----------------------|------------------------------|
| I (low risk) | 0.8 |
| II (medium risk) | 1 |
| III (high risk) | 1.2 |
| IV (exceptional risk) | 1.6 |

- ❑ suggests that the National Annexes should provide more precise values which may differentiate for the various seismic zones of the country
- ❑ alternatively provides a formula to calculate importance factors for a given return period

Seismic demand for industrial facilities in the Eurocodes

Revision of EC8 (ongoing):

- ❑ Appropriate return periods, $T_{LS,CC}$, or performance factors, $\gamma_{LS,CC}$, should be selected based on limit state (LS) and consequence class (CC) of structures.
- ❑ For structures covered by Part 4 (Silos, tanks and pipelines, towers, masts and chimneys), the Significant Damage (SD) limit state is recommended (structure and its ancillary elements are significantly damaged, but both retain their structural integrity with controlled leakage of contents).

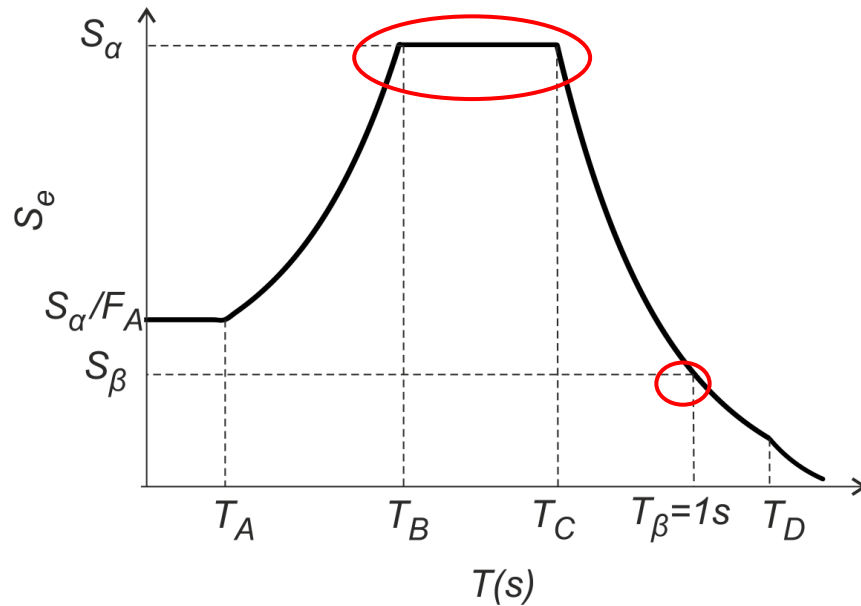
Table 4.2 (NDP) Return periods $T_{LS,CC}$ of seismic action in years

| | Consequence class (CC) | | | |
|----|------------------------|------|-------|-------|
| | CC1 | CC2 | CC3-a | CC3-b |
| NC | 800 | 1600 | 2500 | 5000 |
| SD | 250 | 475 | 1300 | 2500 |
| DL | 50 | 60 | 150 | 250 |

Table 4.3 (NDP) Performance factors $\gamma_{LS,CC}$

| | Consequence class (CC) | | | |
|----|------------------------|-----|-------|-------|
| | CC1 | CC2 | CC3-a | CC3-b |
| NC | 1,2 | 1,5 | 1,8 | 2,2 |
| SD | 0,8 | 1,0 | 1,4 | 1,8 |
| DL | 0,4 | 0,5 | 0,7 | 0,8 |

Implication of the ESHM20 to the seismic design of industrial facilities



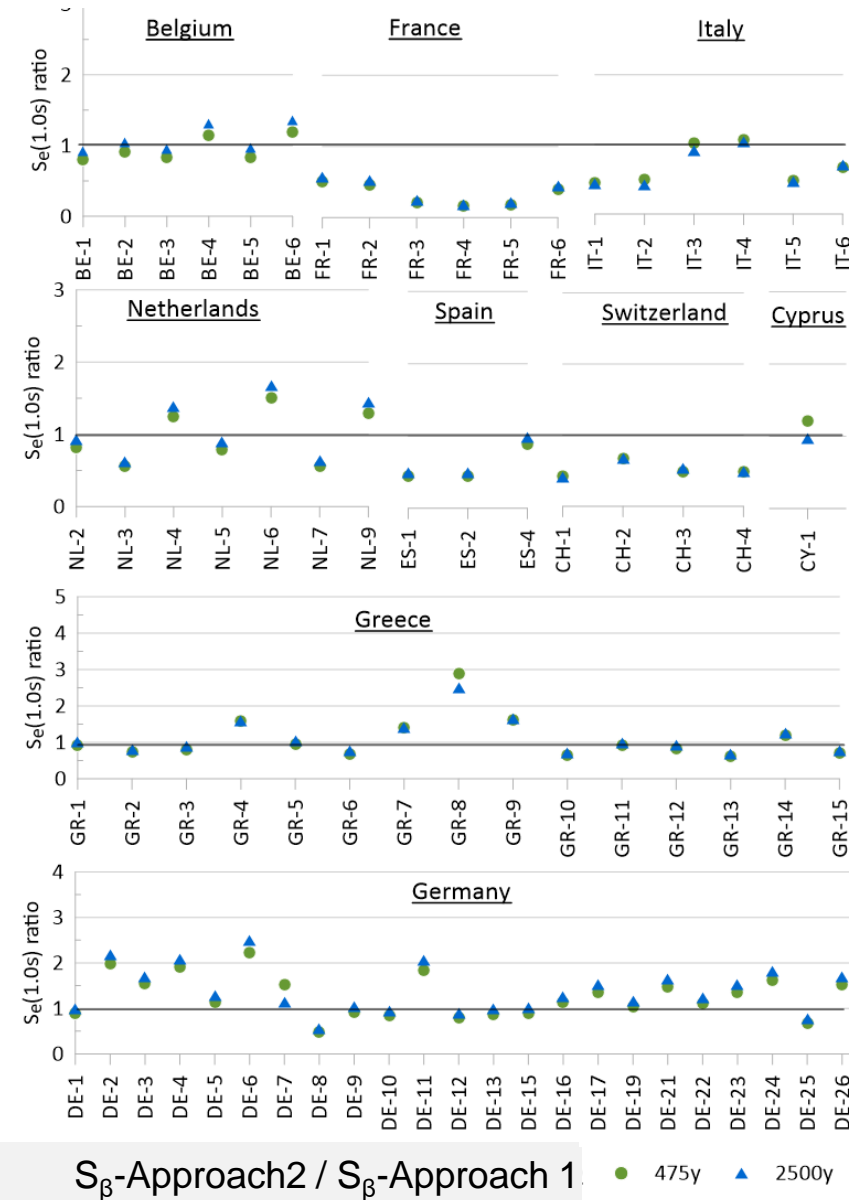
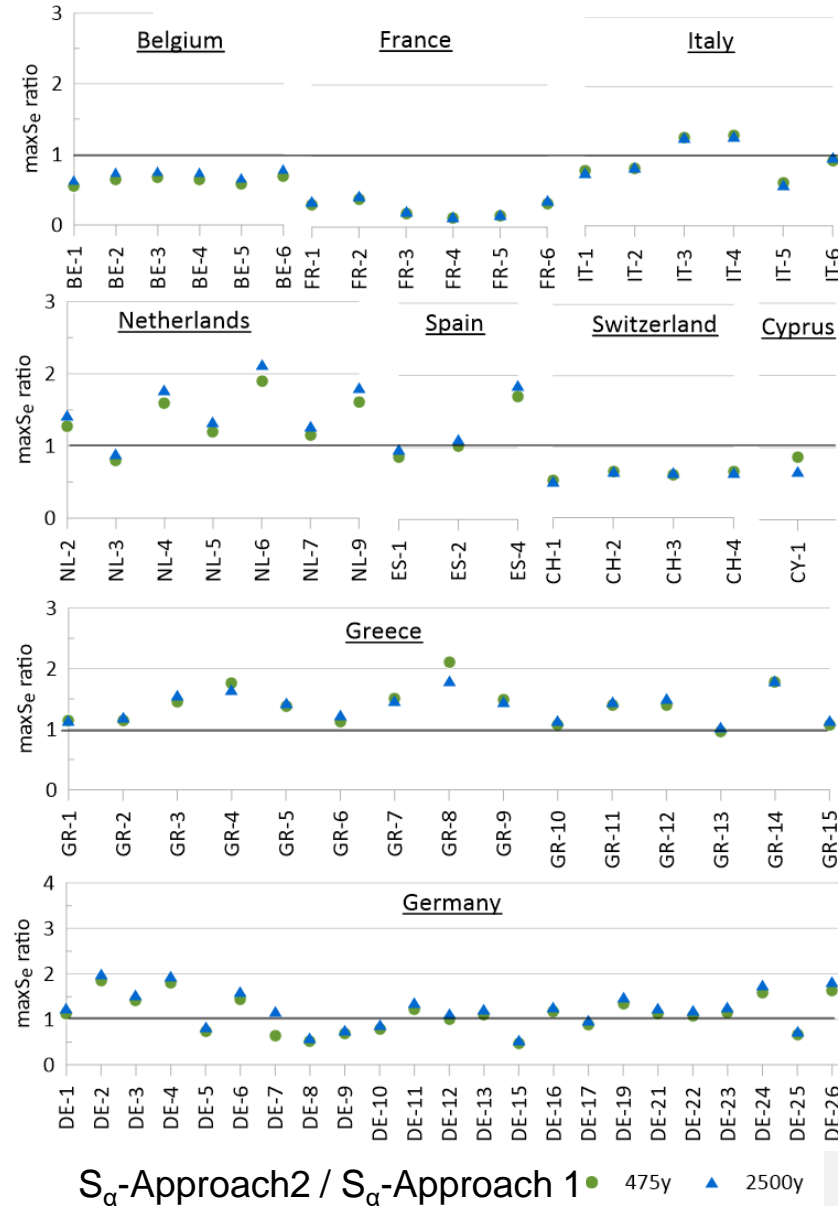
Approach 1 - Current EC8 hazard for 475 years
x importance factor **(1.6)**

Approach 2 - Revised EC8 with $S_{\alpha,475}$ and $S_{\beta,475}$ from ESHM20
x performance factor **(1.8)**

Pitilakis, K., Butenweg, C., Riga, E., Apostolaki, S., Renault, P. (2023). The new seismic hazard model ESHM20 of Europe: Investigating the implications to the seismic design and risk assessment of major industrial facilities across Europe, Bulletin of Earthquake Engineering



Implication of the ESHM20 to the seismic design of industrial facilities

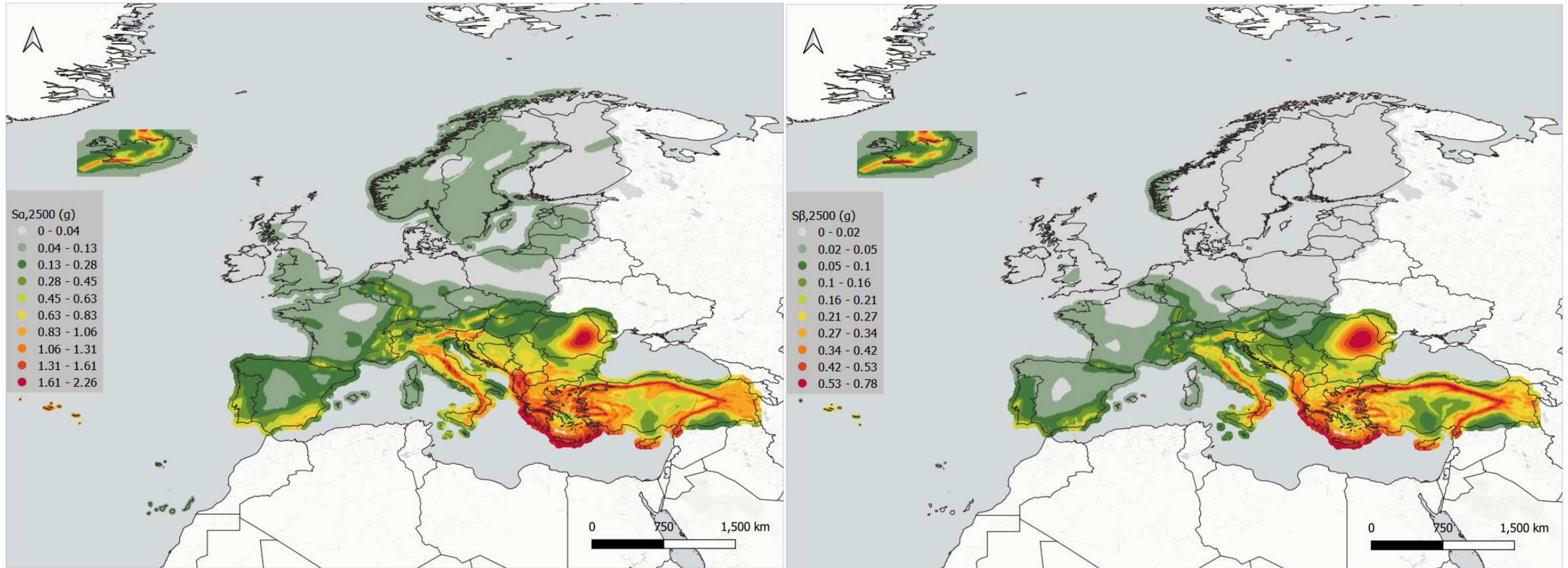


Local site conditions
→ $V_{s,30}$ from site
response model of
ESRM20 (Weatherill
et al., 2021)



Development of $S_{\alpha,RP}$ and $S_{\beta,RP}$ maps for high return periods at European scale

RP = 2500 years



Apostolaki, S., Riga, E., Pitilakis, D. Pitilakis, K. (2024). EC8-compatible seismic hazard maps for high return periods for the design of industrial facilities, 18th World Conference on Earthquake Engineering, June 30-July 5, Milan, Italy (accepted abstract).

Application at Vasilikos Power Station in Cyprus

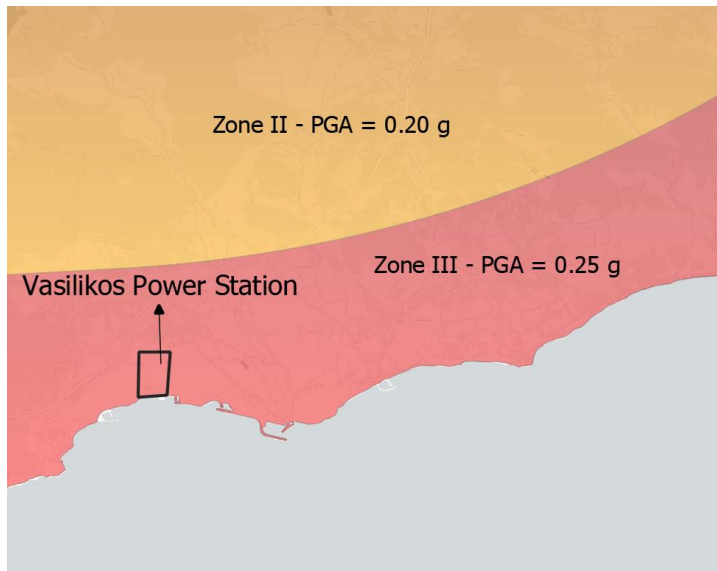
APPLICATION → a hypothetical steel Storage Tank at the Vasilikos Power Station

SEISMIC DESIGN (2500 years return period) →

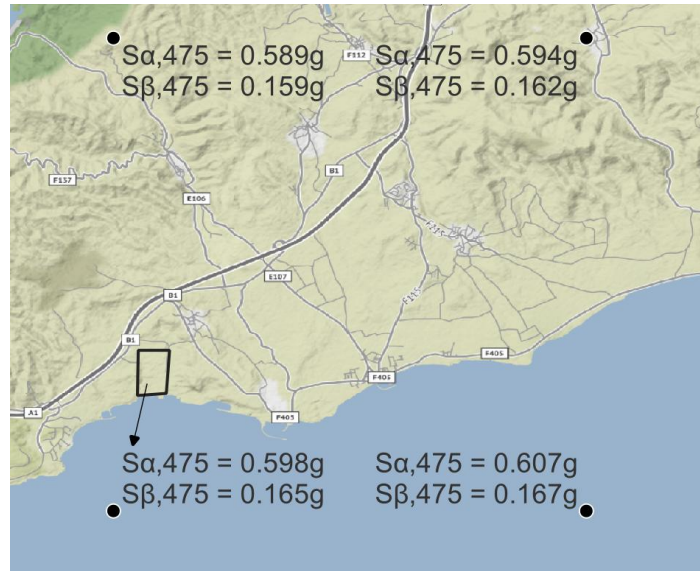
Approach 1 - Current EC8 hazard for 475 years x importance factor **(1.6)**

Approach 2 - Revised EC8 with $S_{\alpha,475}$ and $S_{\beta,475}$ from ESHM20 x performance factor **(1.8)**

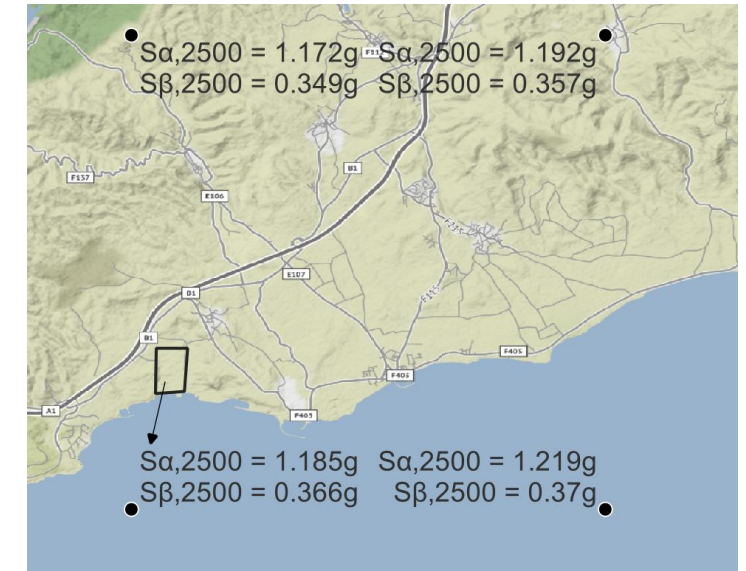
Approach 3 - Revised EC8 with $S_{\alpha,2500}$ and $S_{\beta,2500}$ **from developed hazard maps**



Seismic hazard map of the current EC8
Approach 1



$S_{\alpha,475}$ and $S_{\beta,475}$ from ESHM20
Approach 2



Developed $S_{\alpha,2500}$ and $S_{\beta,2500}$
Approach 3

Application at Vasilikos Power Station in Cyprus

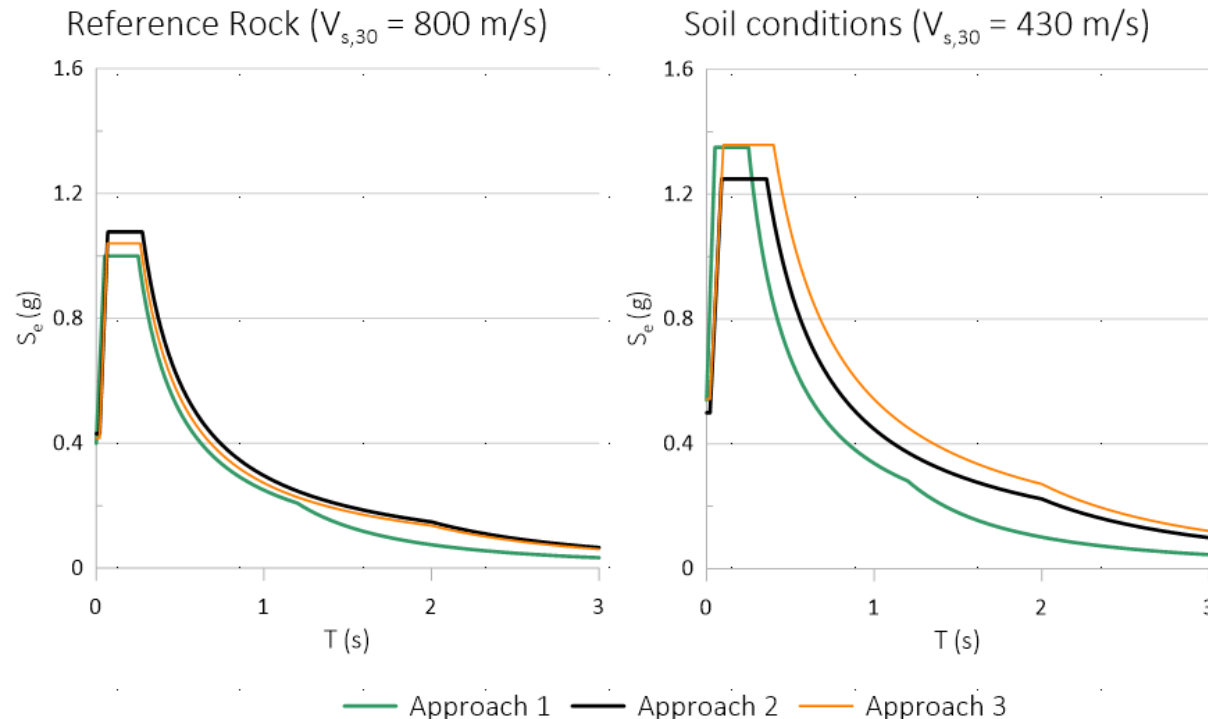
- ❑ Elastic response spectra for **rock conditions** and **considering site effects** for the return period of **2500 years**

$V_{s,30} \approx 430$ m/s from site response model of ESRM20 (Weatherill et al., 2021) - Soil categorization:

- Soil type B based on the current EC8
- Soil type B based on the revised EC8 considering the intermediate depth class

PGA (g):

- 0.40 (Approach 1)
- 0.43 (Approach 2)
- 0.42 (Approach 3)

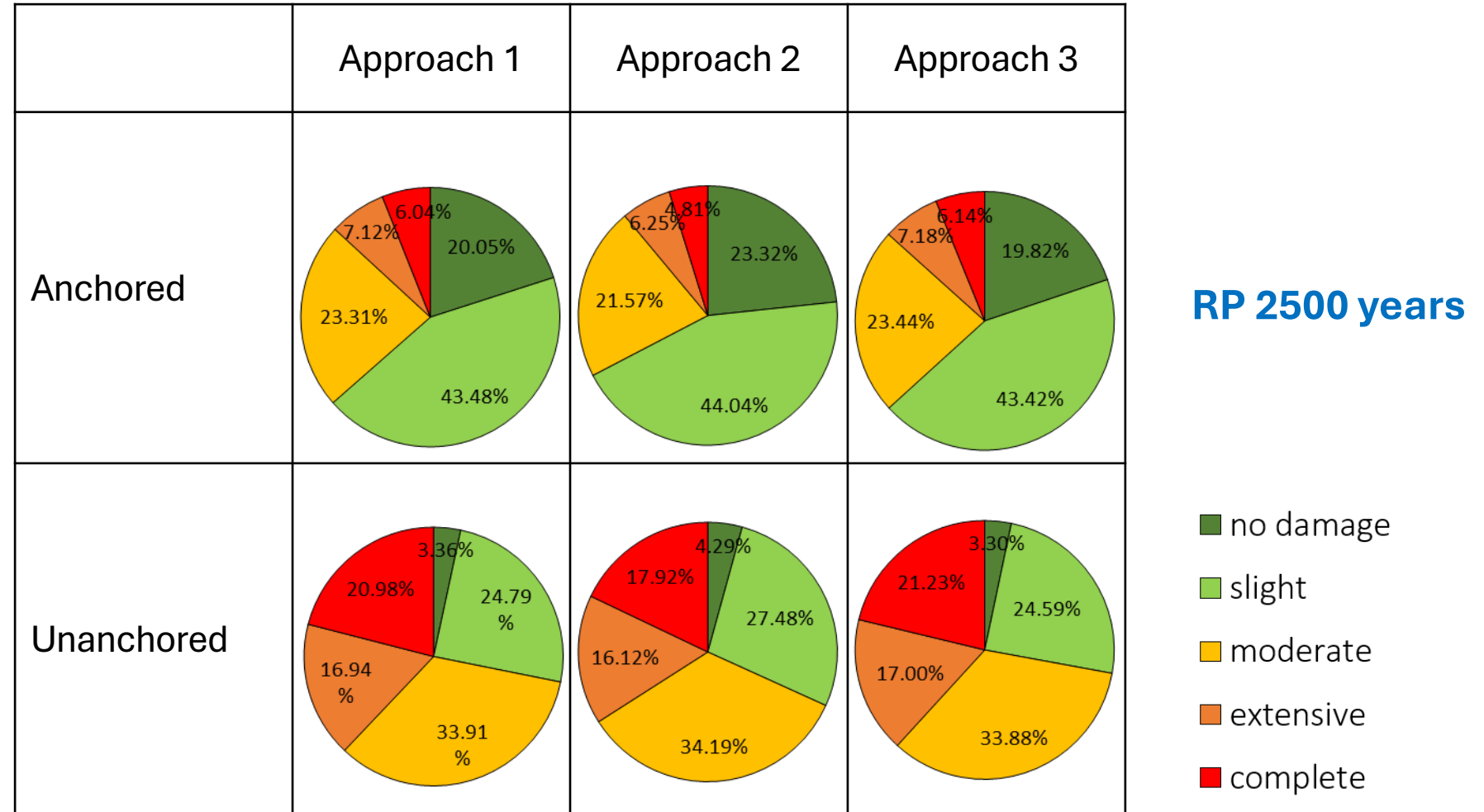


PGA (g):

- 0.54 (Approach 1)
- 0.50 (Approach 2)
- 0.54 (Approach 3)

Application at Vasilikos Power Station in Cyprus

Expected probabilities of being in each damage state for the hypothetical steel storage tank



Outline

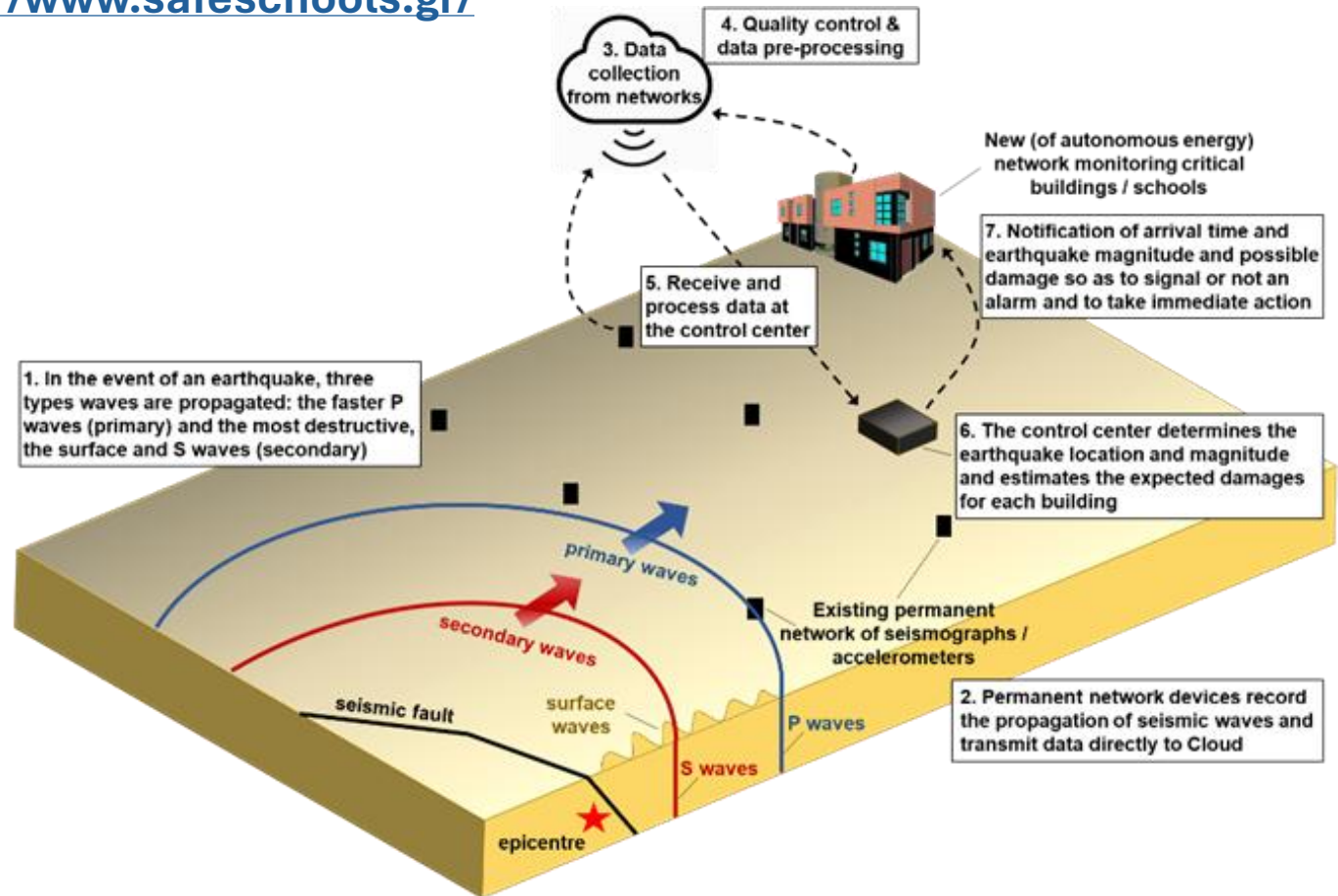
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 - ☐ Risk assessment at urban environment: Thessaloniki
 - ☐ Critical industrial facilities
- ☐ Vulnerability and seismic risk assessment of critical infrastructures
 - ☐ Early warning and real time risk assessment (SafeSchools)
 - ☐ Risk assessment of schools (RiskSchools)
 - ☐ Systemic seismic analysis of critical infrastructures at urban scale

SafeSchools: An earthquake early warning and early damage assessment tool for critical buildings

<https://www.safeschools.gr/>

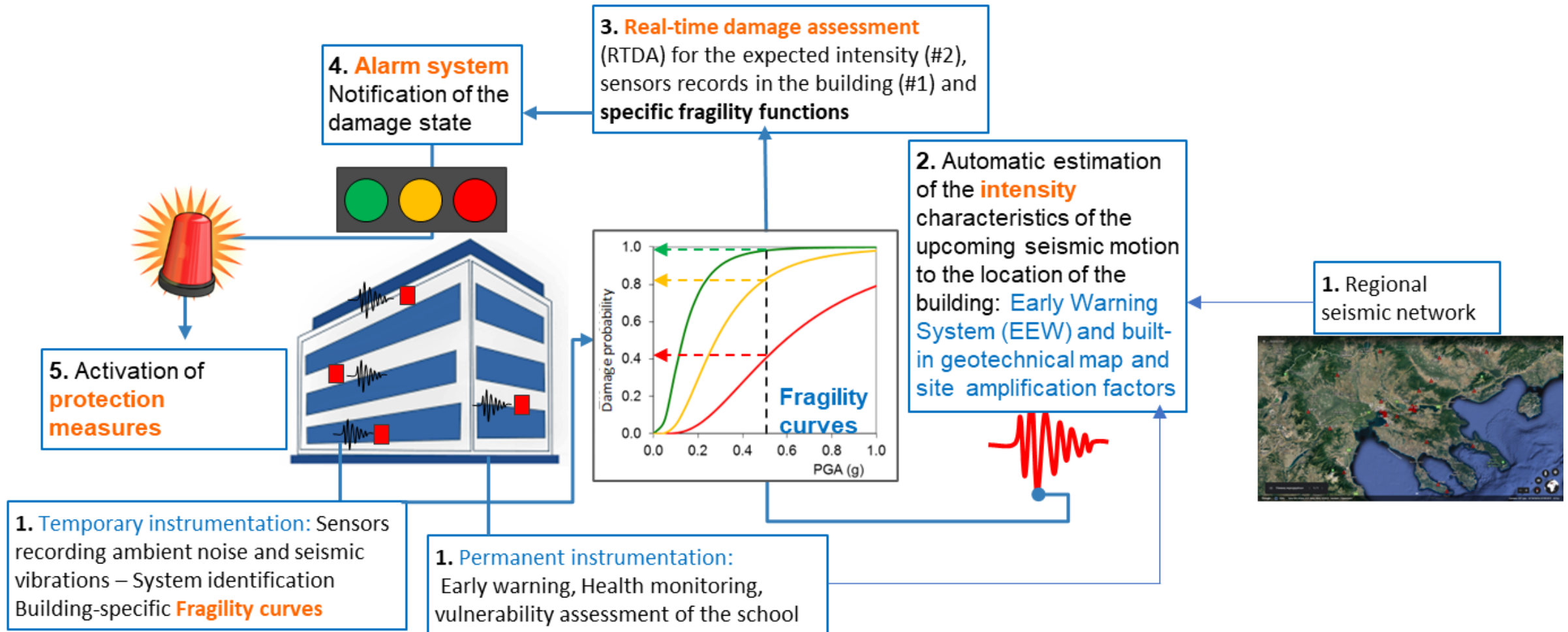
Goal:

To develop an innovative system for the **earthquake early warning** and **real-time risk assessment** of critical buildings against **earthquakes**, which can be immediately extended to other critical infrastructures and **natural disasters**.

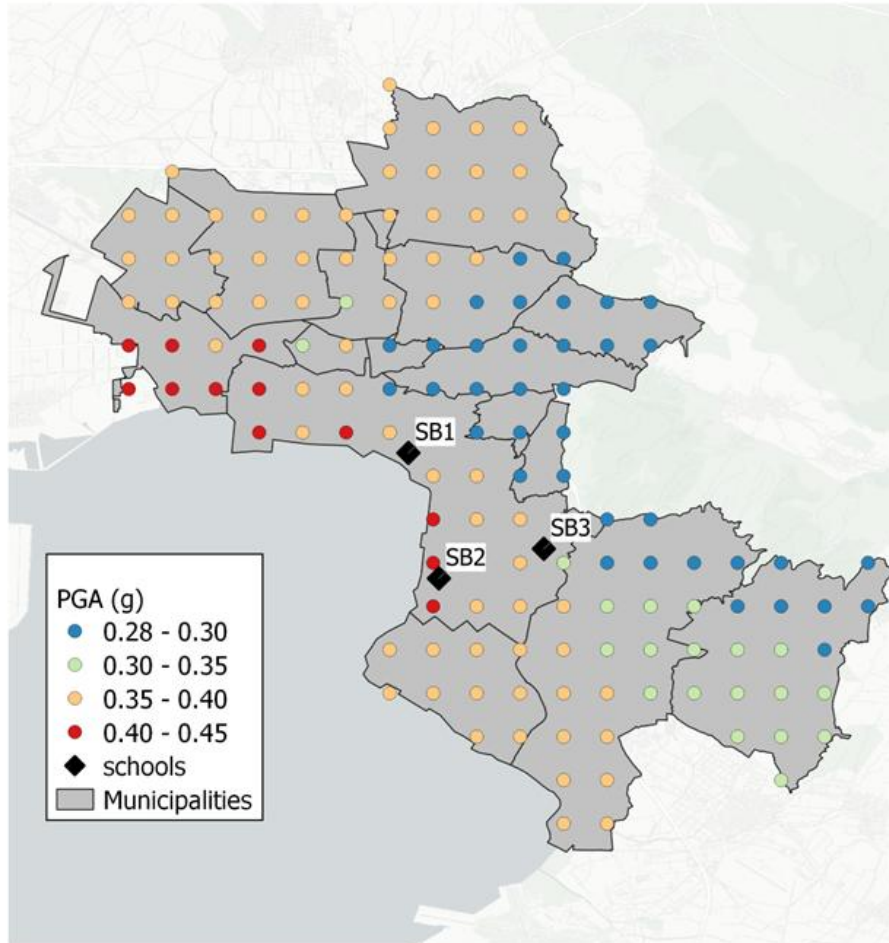


Pitilakis, K., Fotopoulou, S., Manakou M., Karafagka S., Petridis C., Raptakis D., Pitilakis D., 2024. Effective seismic risk reduction of critical facilities: a utopia, a wishful idea, or a realistic challenge? The SafeSchools project, Bulletin of Earthquake Engineering (under review).

Concept detailing



Application to school buildings



SB1



SB2

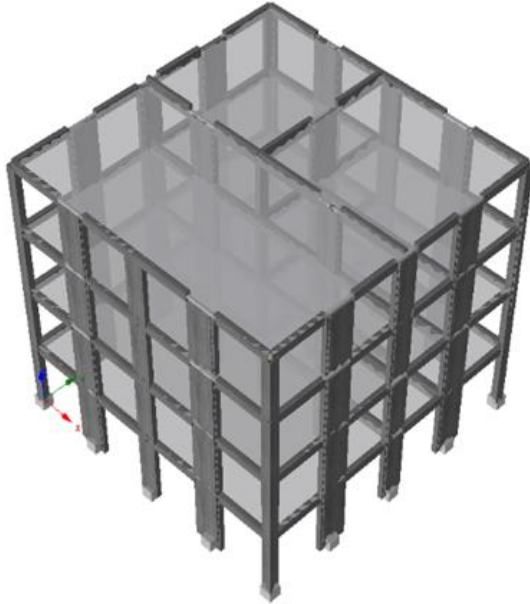


SB3

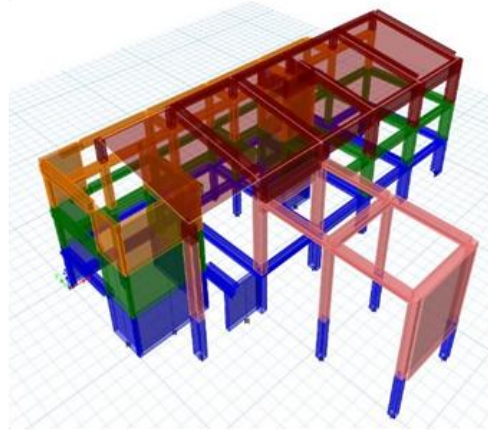


Application to school buildings

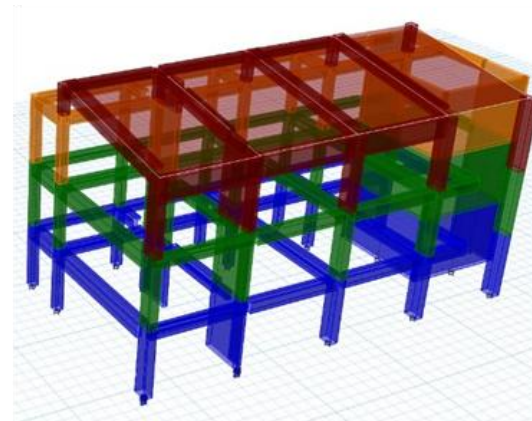
FE model of SB1



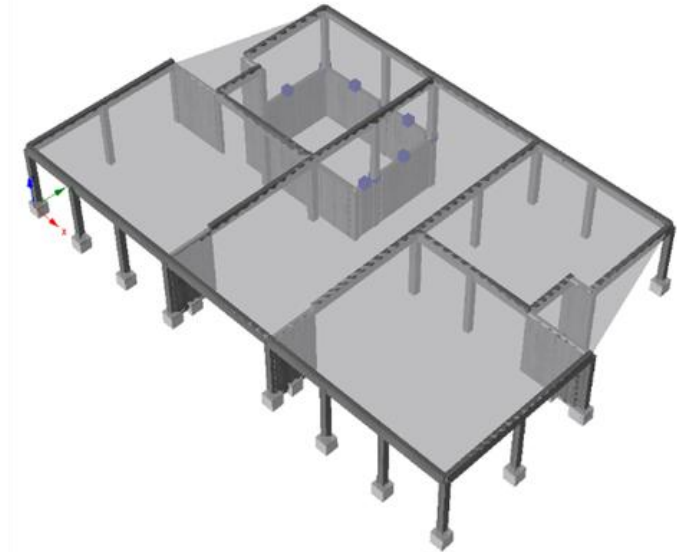
FE model of SB2- part A



FE model of SB2- part B

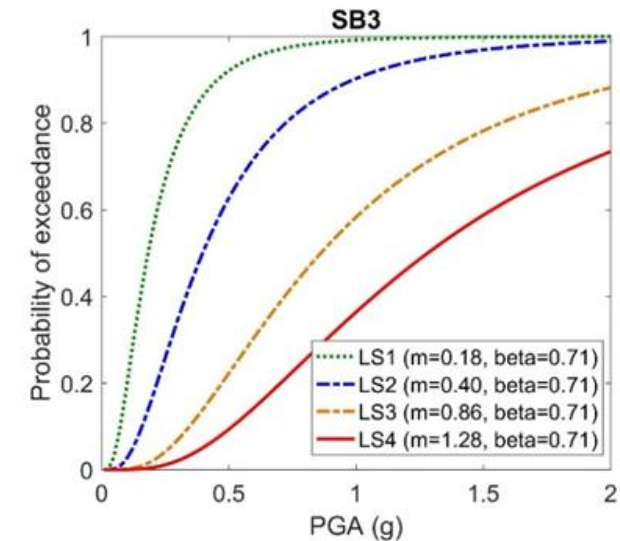
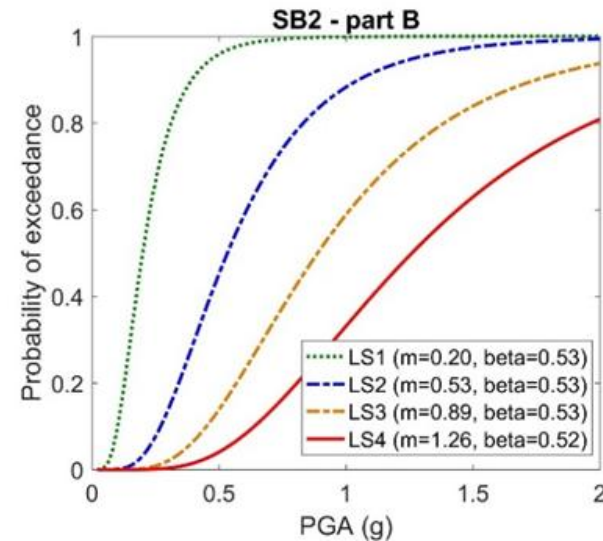
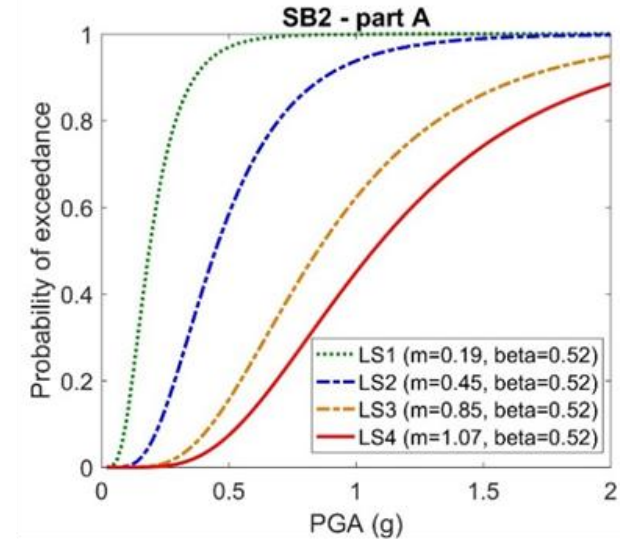
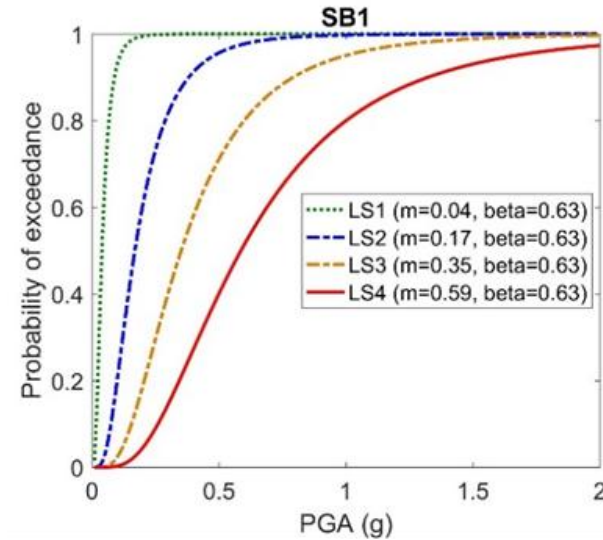


FE model of SB3



Building-specific fragility curves

School building-specific fragility curves may be different from generic ones



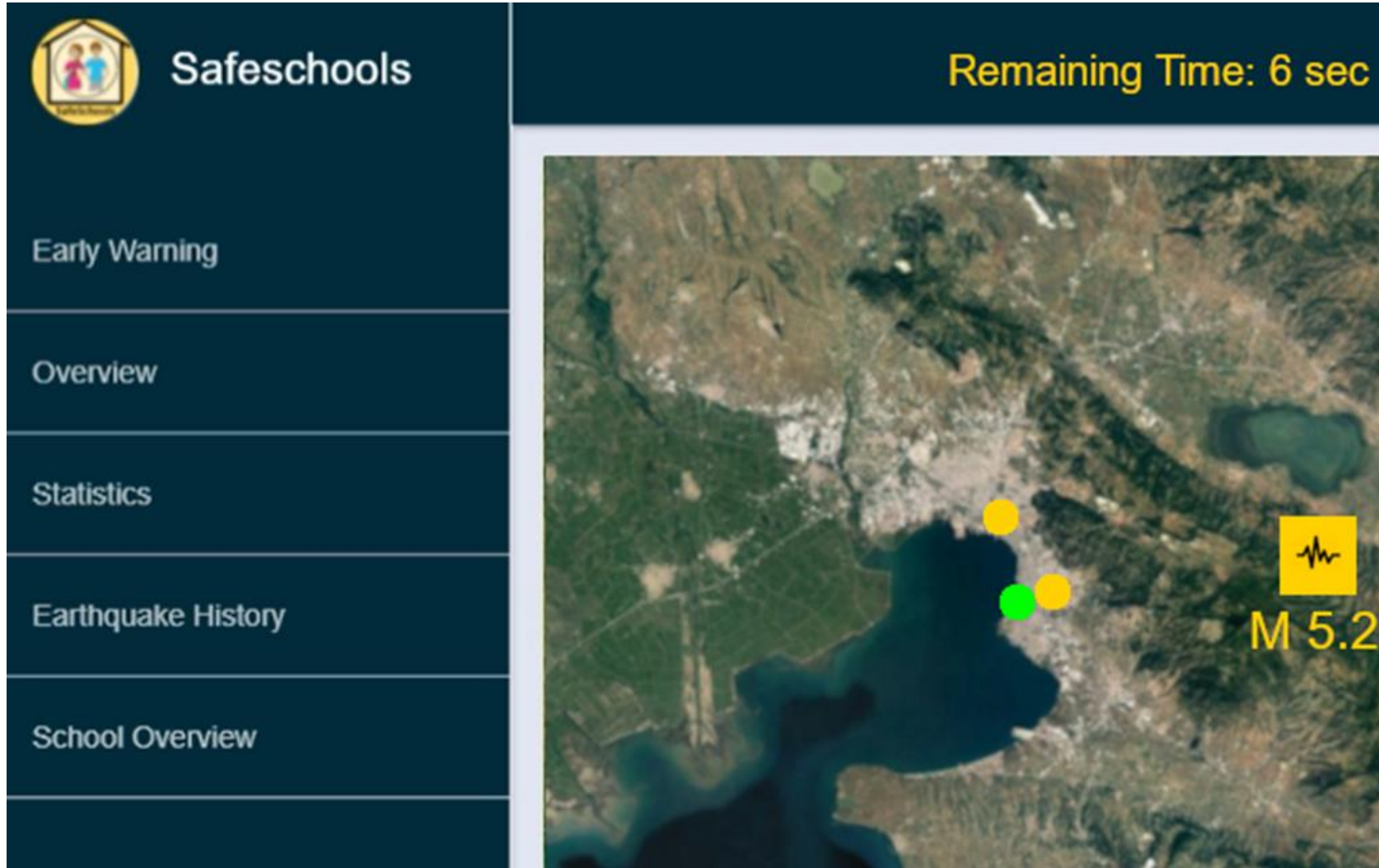
Real-time risk assessment

- ☐ The system is capable to estimate the expected damage and loss level using the vulnerability curves assigned for each building, (generic or building specific) providing immediately a warning to the end-users for the incoming earthquake event based on the level of expected intensity and risk.
- ☐ All information is saved to a central database in a control centre
- ☐ A three-color building safety categorization is assigned:
 - ☐ “green” for none or slight non-structural damages
 - ☐ “yellow” for moderate structural damages and
 - ☐ “red” for heavy or very heavy damages including partially and total collapse

Real-time risk assessment

- ❑ The overall system informs/warns in two stages (levels):
 - ❑ at the first level, it informs each school (through automation in the form of a siren) and the control center (e.g. through a light indicator) about the intensity level of the upcoming earthquake, in terms of M and PGA and
 - ❑ at the second level, with a short time delay, it informs the responsible persons (e.g. Civil Protection, Municipality, school director) about the level of the expected damages for **each school** (green, yellow, red).

Visualization, alert, and communication



SafeSchools

<https://www.safeschools.gr/>

- ❑ An innovative system for earthquake **early warning and real-time damage** assessment, specifically designed to protect critical buildings like **schools**
- ❑ Generic or improved building-specific vulnerability curves may be applied using monitoring data from small seismic events and ambient noise measurements
- ❑ Design and development of low-cost accelerometric stations (MEMs)
- ❑ Efficient stakeholder-specific visualization and alarming platform
- ❑ Implementation in number of school buildings in Thessaloniki, Greece

RiskSchools system

<https://riskschools.gr/>

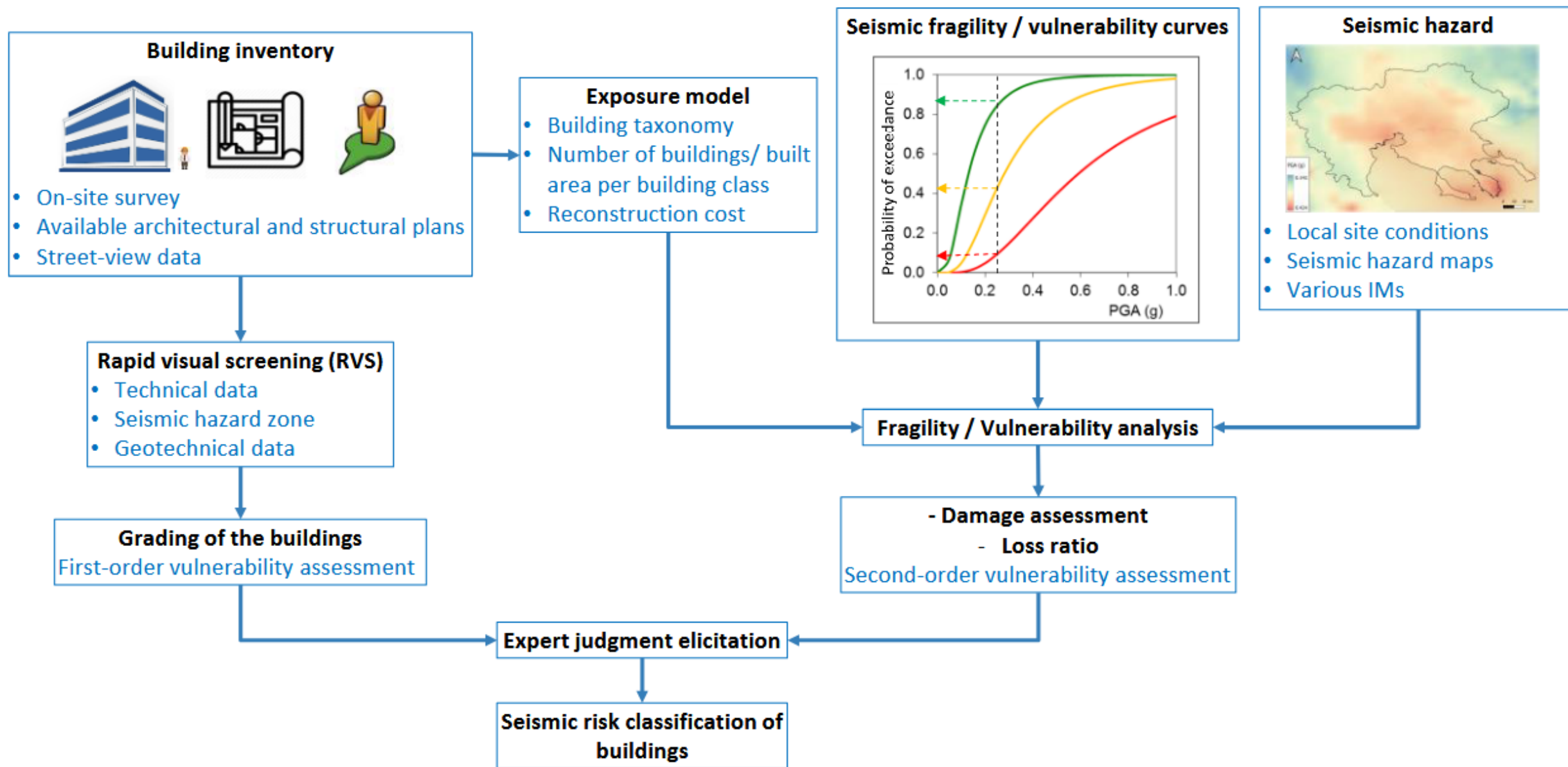
- ❑ RiskSchools **system**
- ❑ RiskSchools **smartphone app** for the rapid visual screening of school buildings
- ❑ RiskSchools **platform**
- ❑ RiskSchools **application in Central Macedonia Greece**

Karafagka, S., Riga E., Oikonomou G., Karatzetzou A, Fotopoulou, S., Pitilakis D., Pitilakis, K. 2023. RiskSchools: A prioritization-based system for the risk assessment of school buildings combining rapid visual screening smartphone app and detailed vulnerability analysis, Bulletin of Earthquake Engineering (accepted).

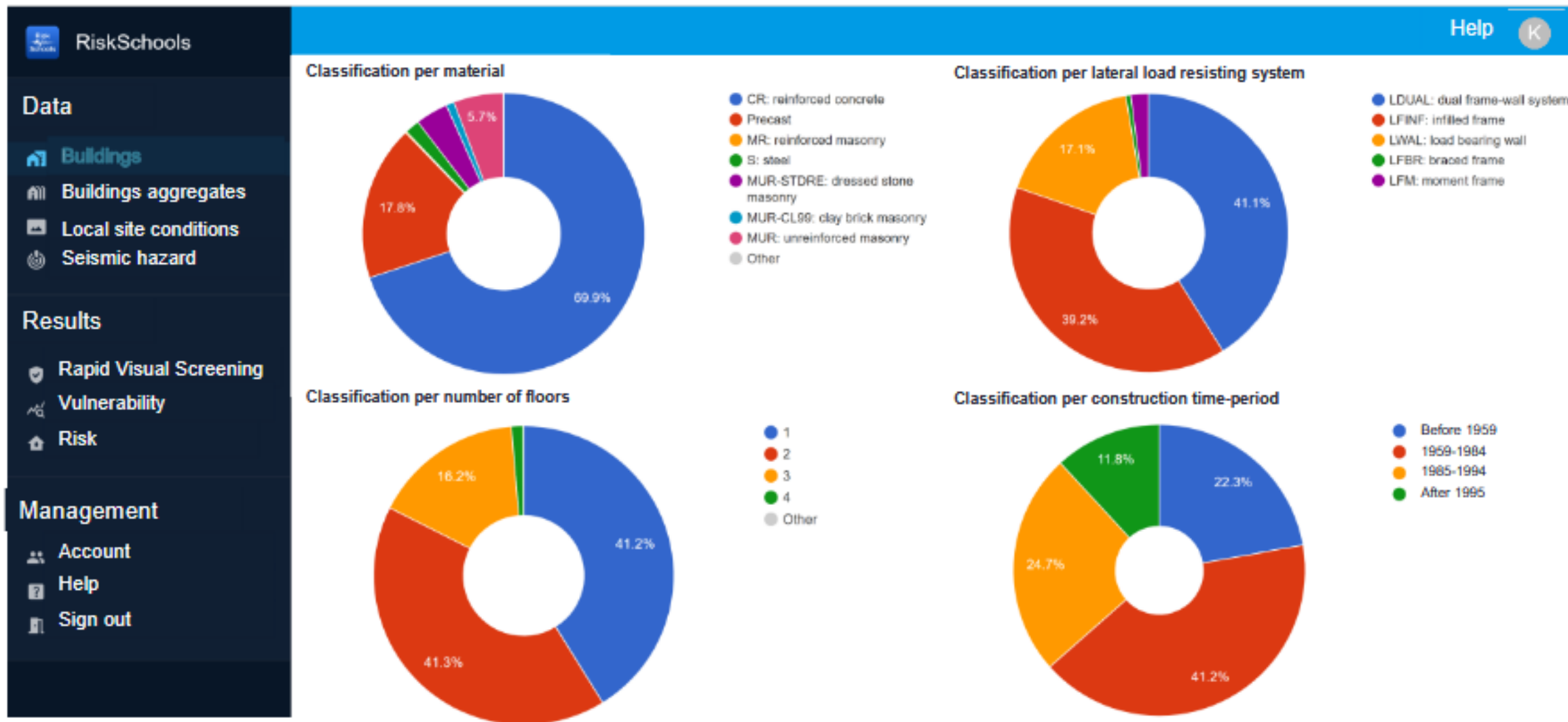
Where RiskSchools could be helpful?

- ☐ Evaluate school buildings seismic risk and retrofiting needs
- ☐ Prioritize risk and design seismic risk mitigation programs for school buildings
- ☐ Planning post-earthquake building safety evaluation efforts
- ☐ Improving the robustness of decision-making procedures and risk mitigation strategies

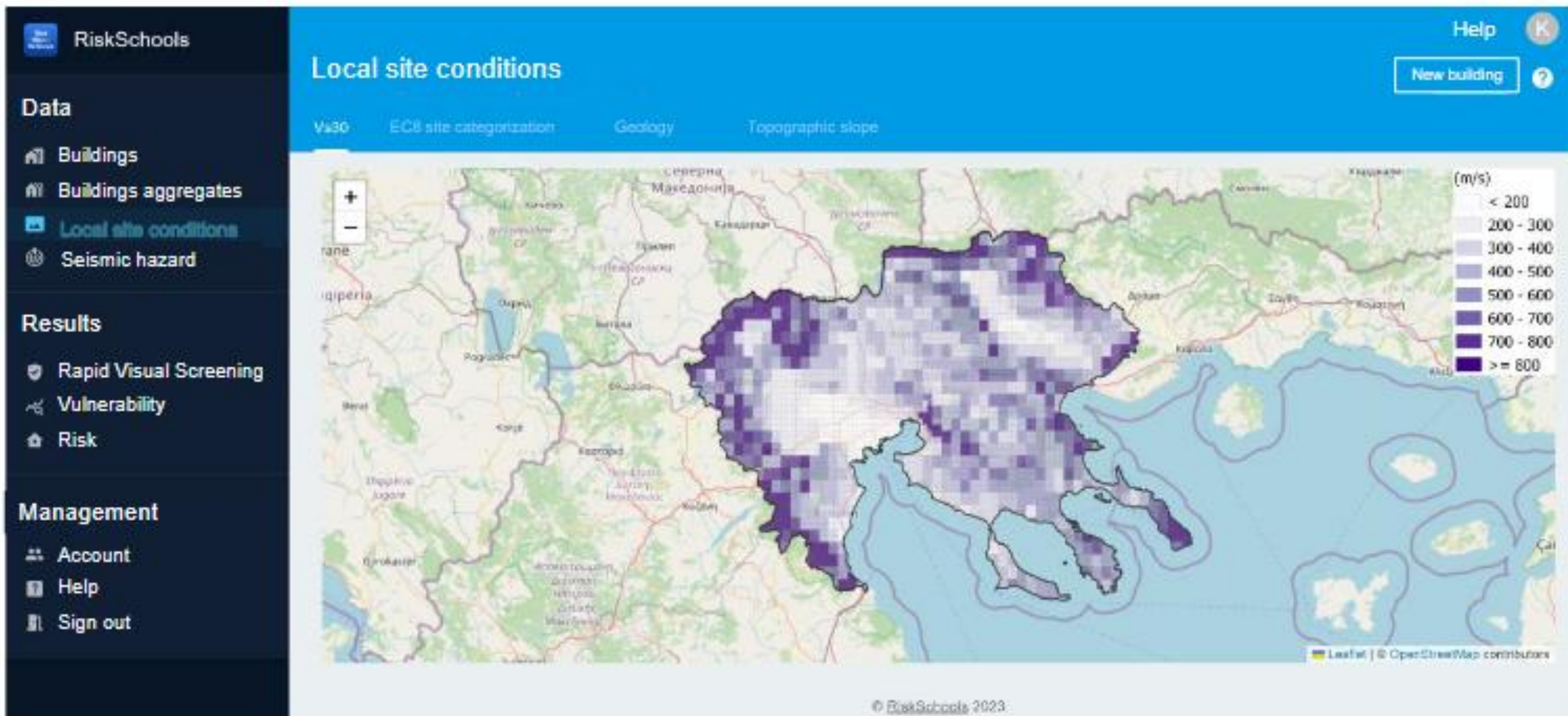
RiskSchools system



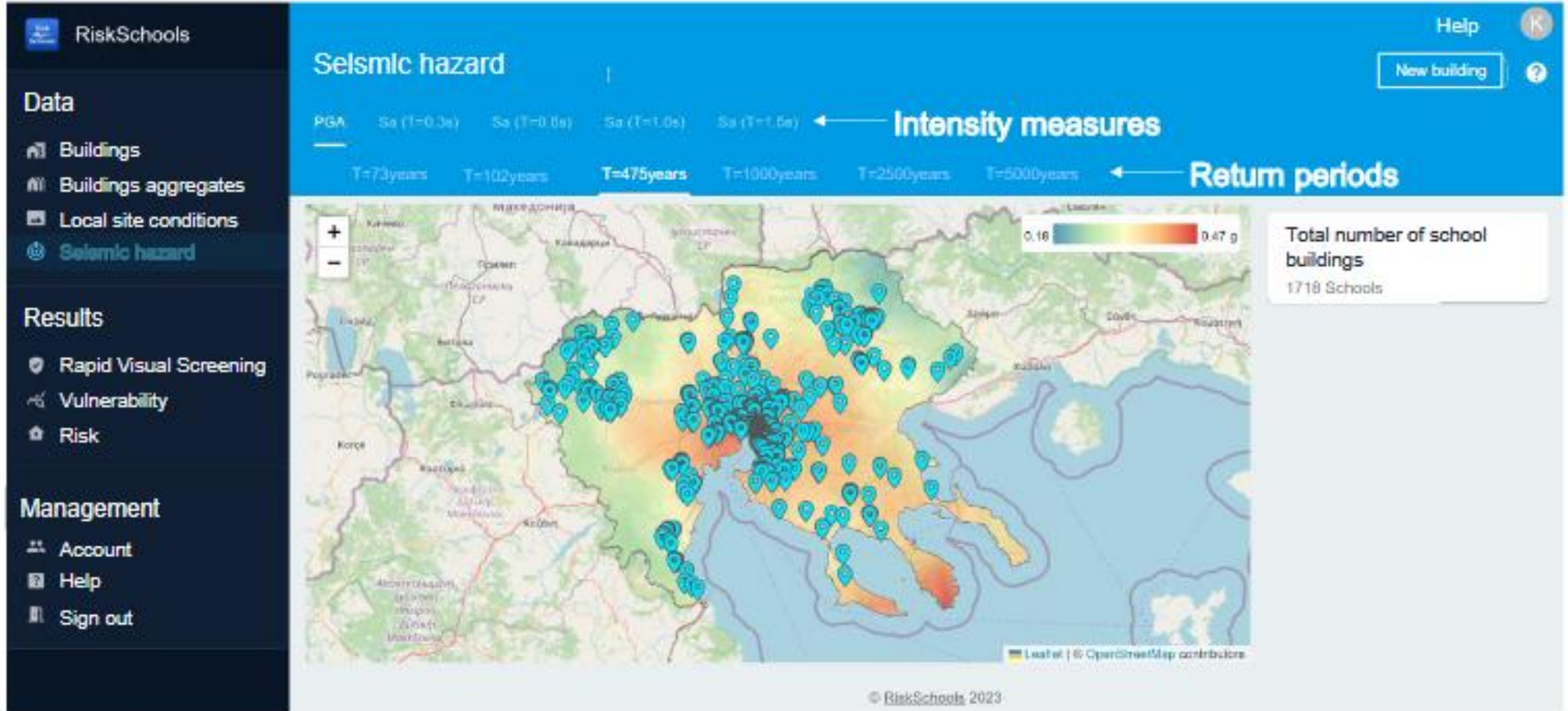
RiskSchools system – Building statistics



RiskSchools system – Local site conditions



RiskSchools system – Seismic hazard



RiskSchools system – Rapid Visual Screening

RiskSchools

Data

- Buildings
- Buildings aggregates
- Local site conditions
- Seismic hazard

Results

- Rapid Visual Screening
- Vulnerability
- Risk

Management

- Account
- Help
- Sign out

Rapid Visual Screening

Filters

Regional unit

Municipality

Material

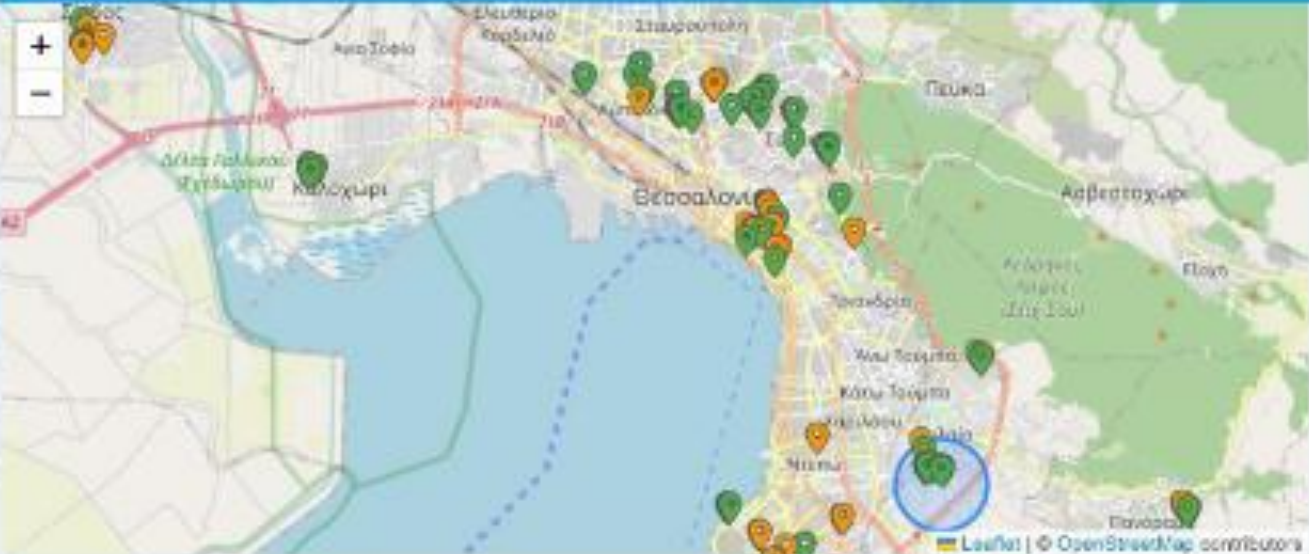
Lateral Load Resisting...

Code level

New building

+

-



Leaflet | © OpenStreetMap contributors

Export

X High School Thessaloniki Building A

Lat, Lon: 40.592751, 22.988062

Material: CR: reinforced concrete

Lateral load resisting system: LDUAL: dual frame-wall system

Code level: CDH

Number of floors: 2

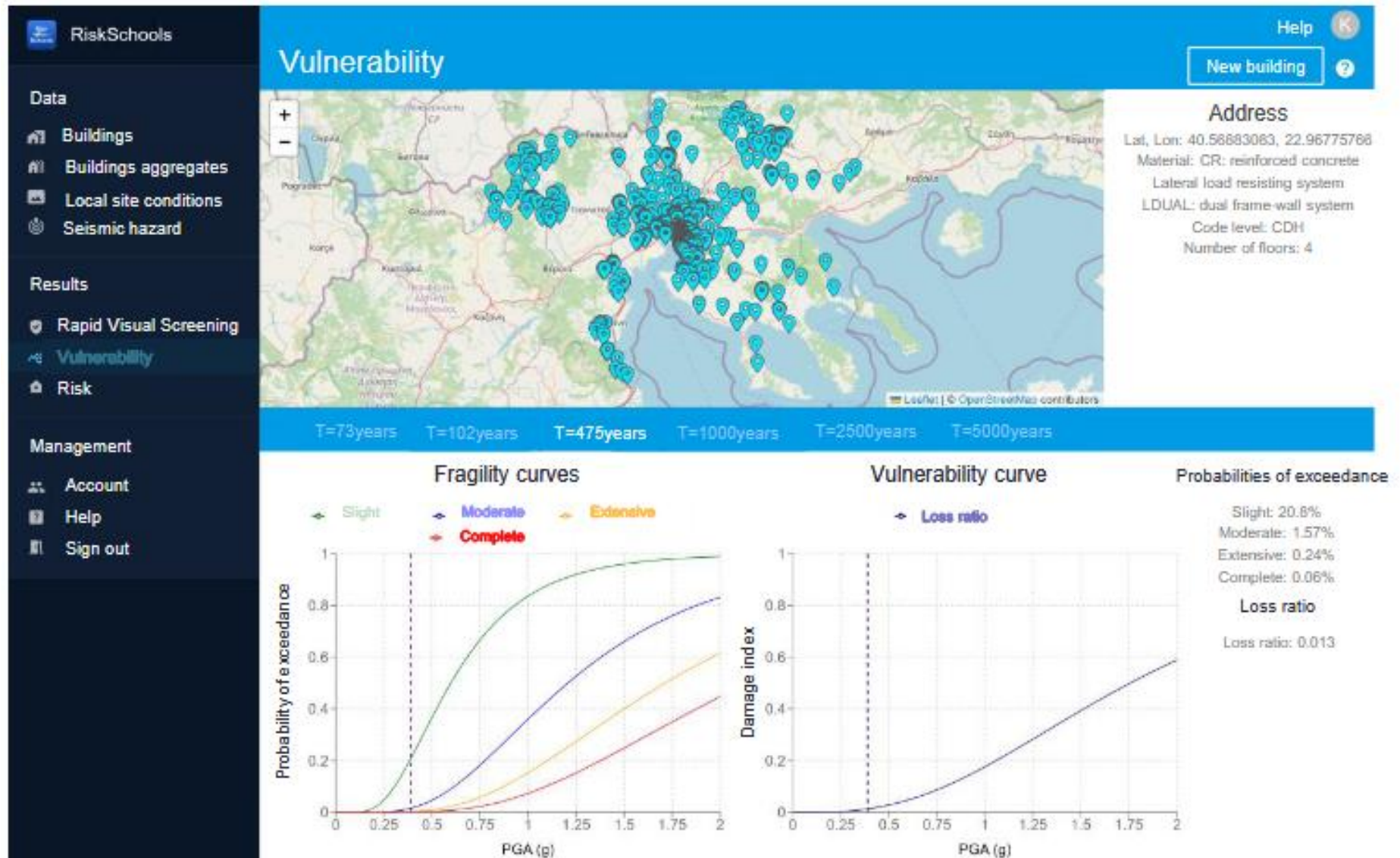
✓

Sufficient

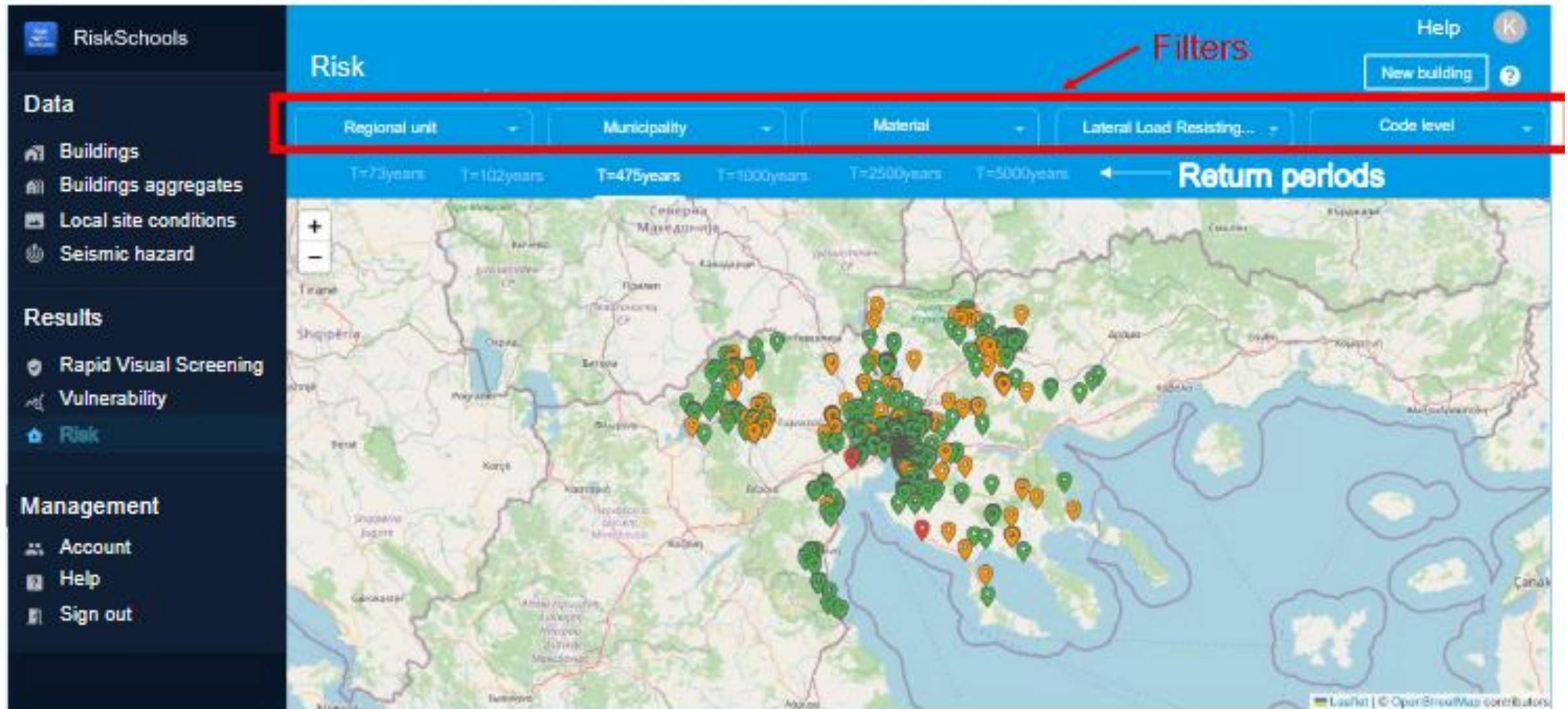
RVS grading: 2.7

| Name | Regional unit | Municipality | RVS grading | RVS result |
|---------------------------------------|---------------|-------------------|-------------|------------------------------------|
| X High School Thessaloniki Building A | Thessaloniki | Pylaia-Chortiatis | 6.2 | <div>✓</div> <div>Sufficient</div> |
| X High School Thessaloniki | Thessaloniki | Thessaloniki | 6.2 | <div>✓</div> <div>Sufficient</div> |

RiskSchools system - Vulnerability

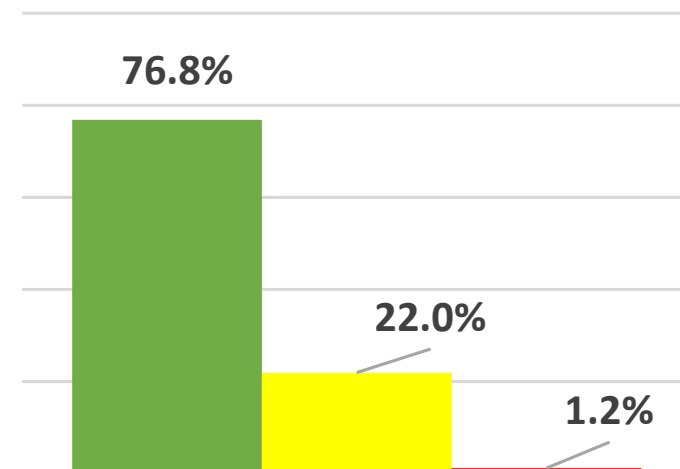
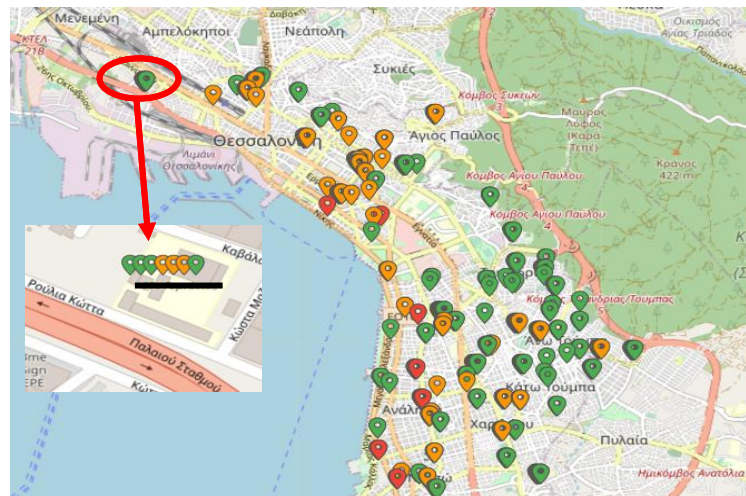
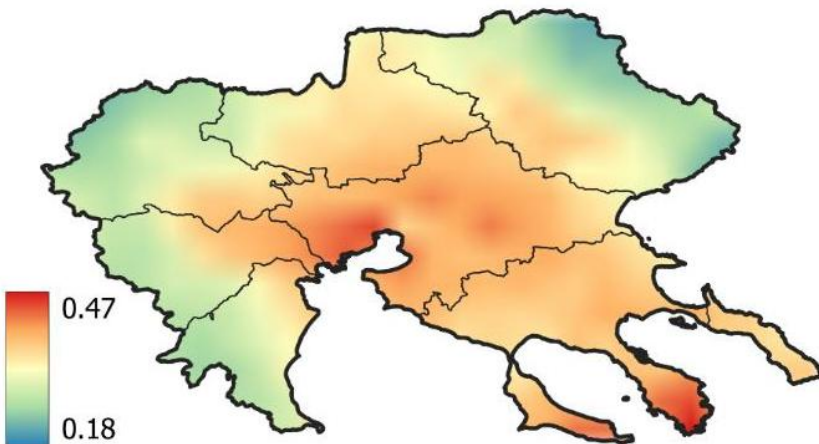


RiskSchools system - Risk

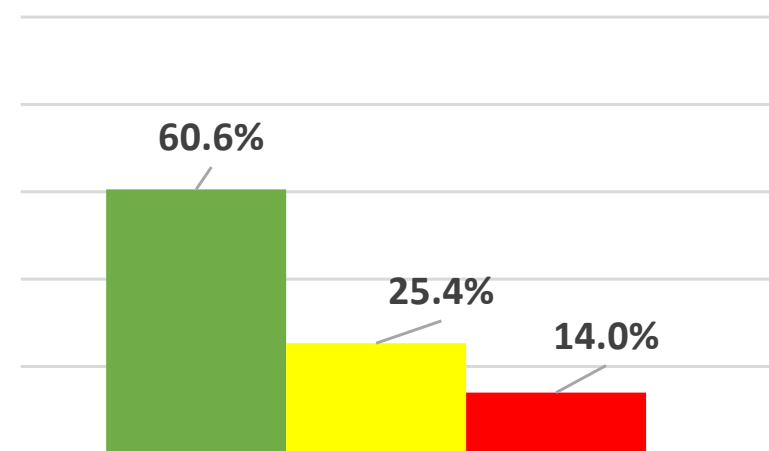
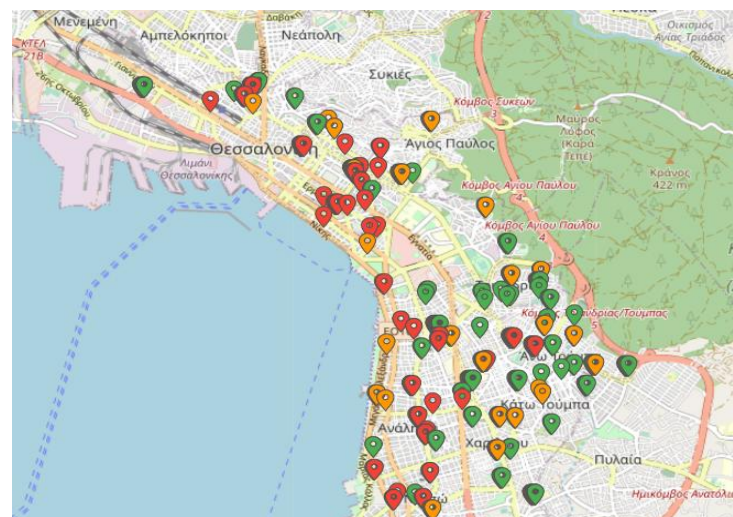
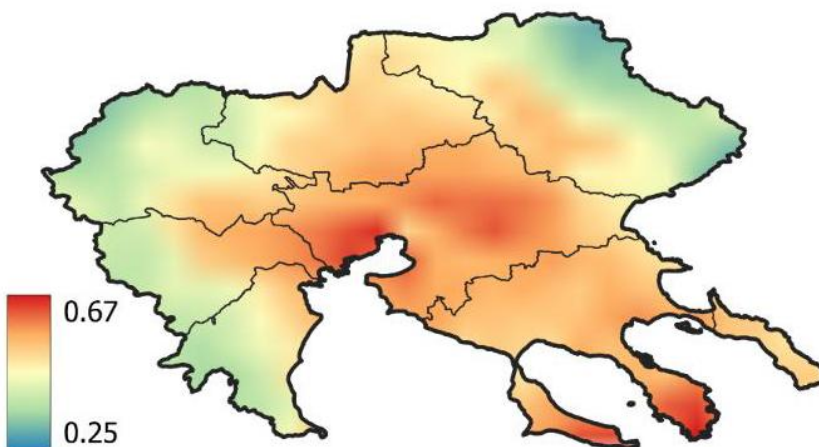


Application to the school buildings of Central Macedonia

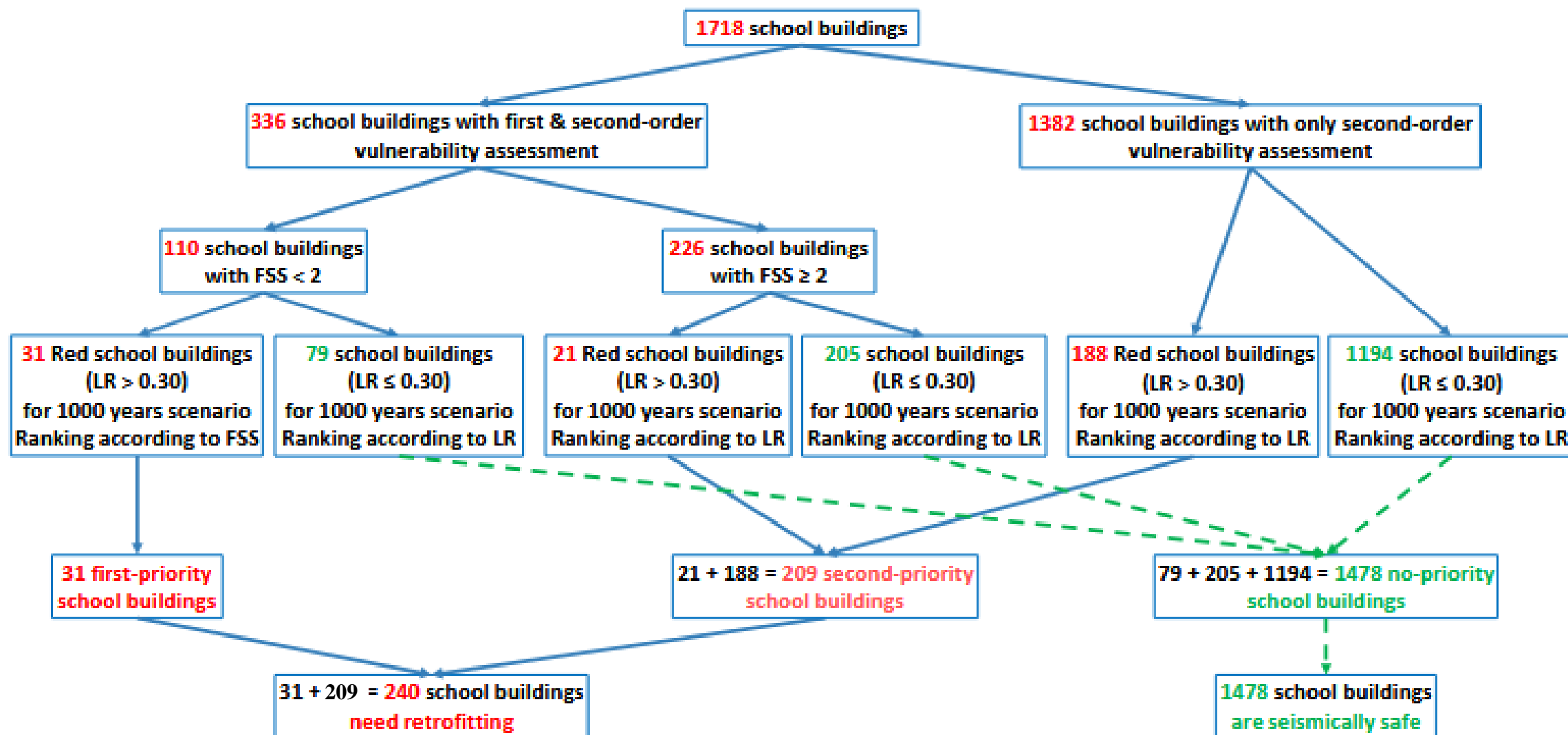
T = 475 years



T = 1000 years



Application to the school buildings of Central Macedonia





Application to the school buildings of Central Macedonia



Systemic seismic risk analysis



Pitilakis, K., Franchin, P., Khazai, B. and Wenzel, H. eds., 2014. SYNER-G: systemic seismic vulnerability and risk assessment of complex urban, utility, lifeline systems and critical facilities: methodology and applications . Springer.

Pitilakis, K., Crowley, H. and Kaynia, A.M. eds., 2014. SYNER-G: typology definition and fragility functions for physical elements at seismic risk. Geotechnical, Geological and Earthquake Engineering. Springer.

Implementation of Infrastructure Risk to OpenQuake

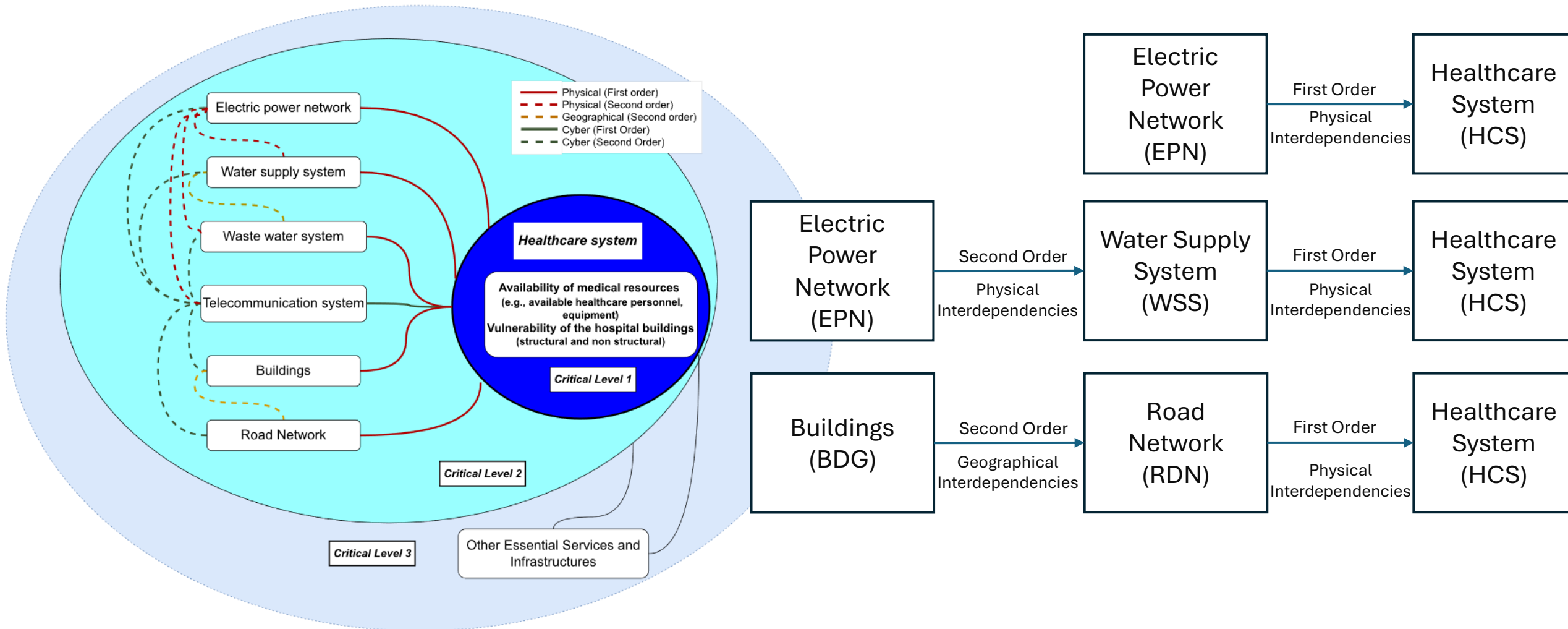


OpenQuake is a **widely accepted, open** tool (PYTHON based); possess a **largest hazard library with maximum number of GMPEs; compute risk and vulnerability of the buildings.**

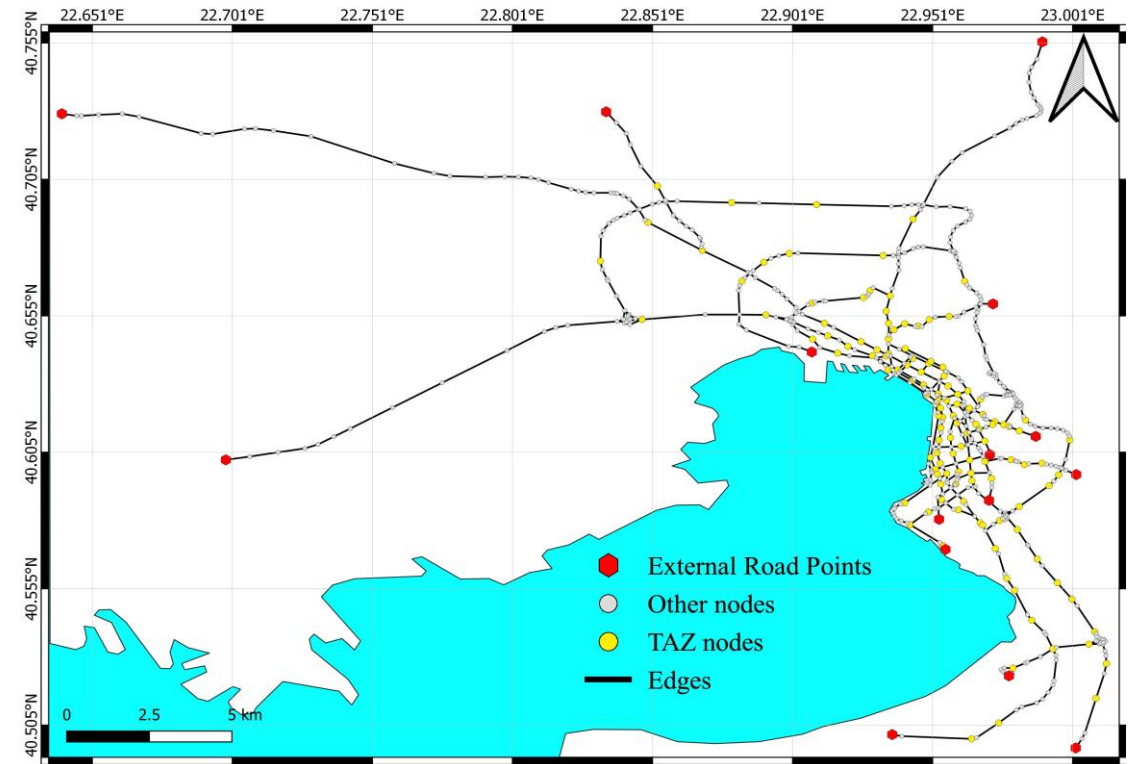
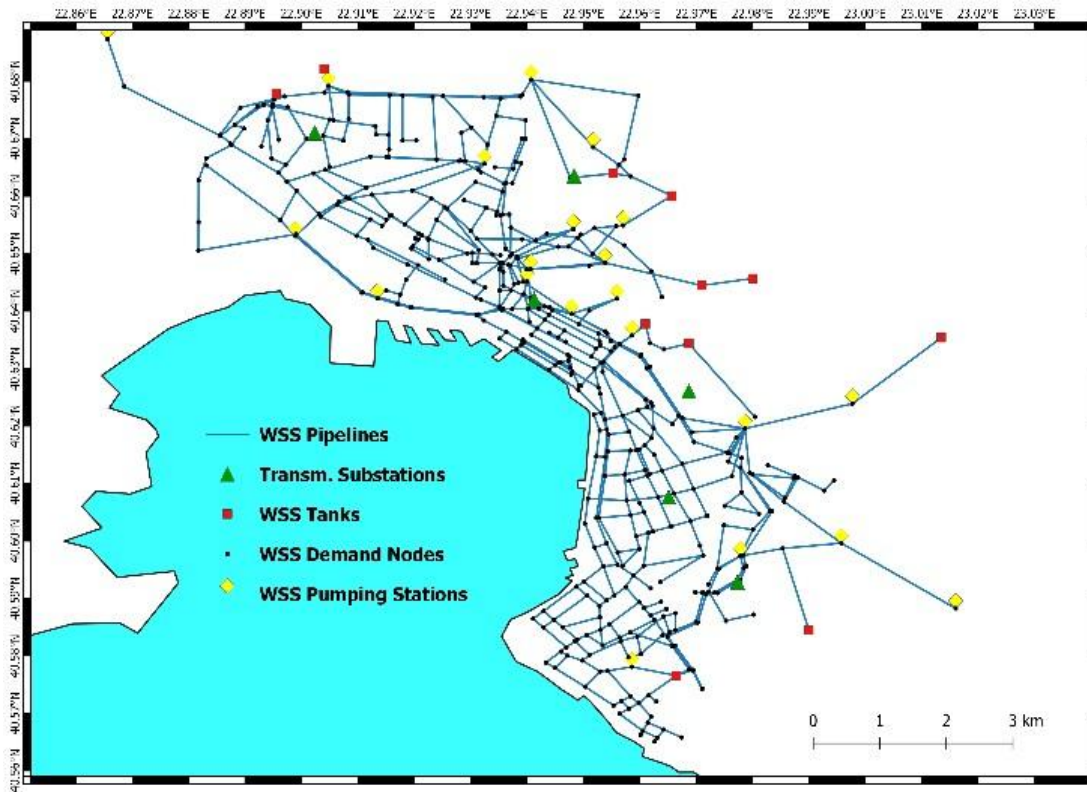
Combination of the capabilities of this powerful platform with **infrastructure and systemic risk** assessment is expected to gain wide and **extensive application around the globe**

Systemic Seismic Risk of Critical Infrastructures at Urban Scale

Interdependencies with respect to the **healthcare system**



Water, electrical power and road systems in Thessaloniki

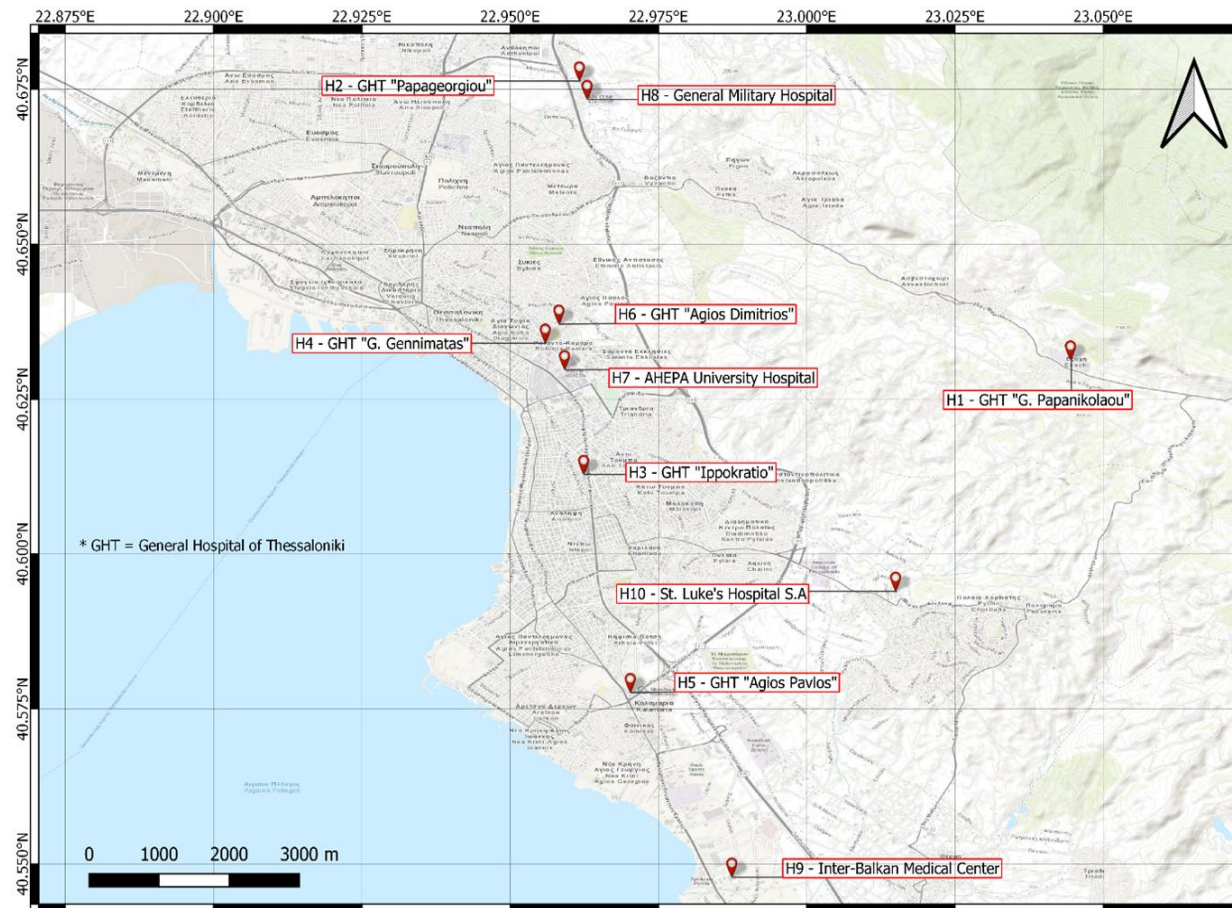


Local Site Conditions to System Performance



Spatial distribution of Vs.30 models of Thessaloniki according to USGS slope-based model (left) and measured values (right)

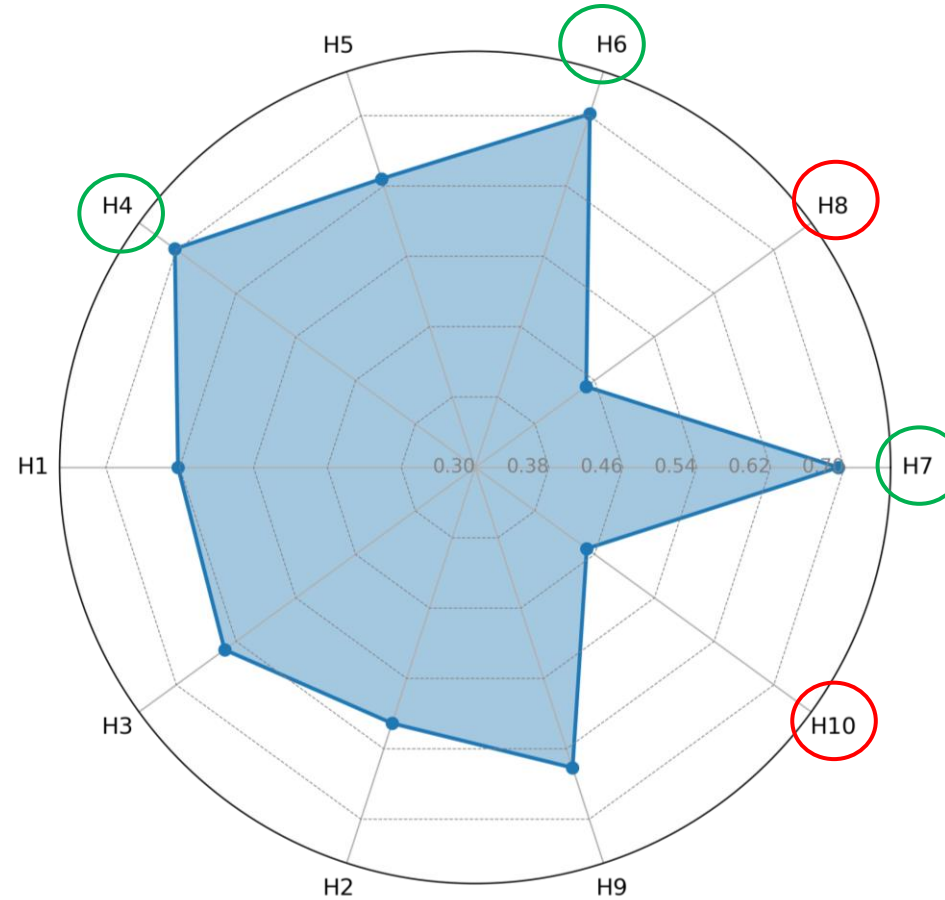
Performance of the Hospitals



| | |
|-----------------------------|-----|
| GHT "G. Papanikolaou" | H1 |
| GHT "Papageorgiou" | H2 |
| GHT "Ippokratio" | H3 |
| GHT "G. Gennimatas" | H4 |
| GHT "Agios Pavlos" | H5 |
| GHT "Agios Dimitrios" | H6 |
| AHEPA University Hospital | H7 |
| General Military Hospital | H8 |
| Inter-Balkan Medical Center | H9 |
| St. Luke's Hospital | H10 |

Impact from various external interdependent infrastructures to each hospital considering the effect of interdependencies

Performance of the Hospitals

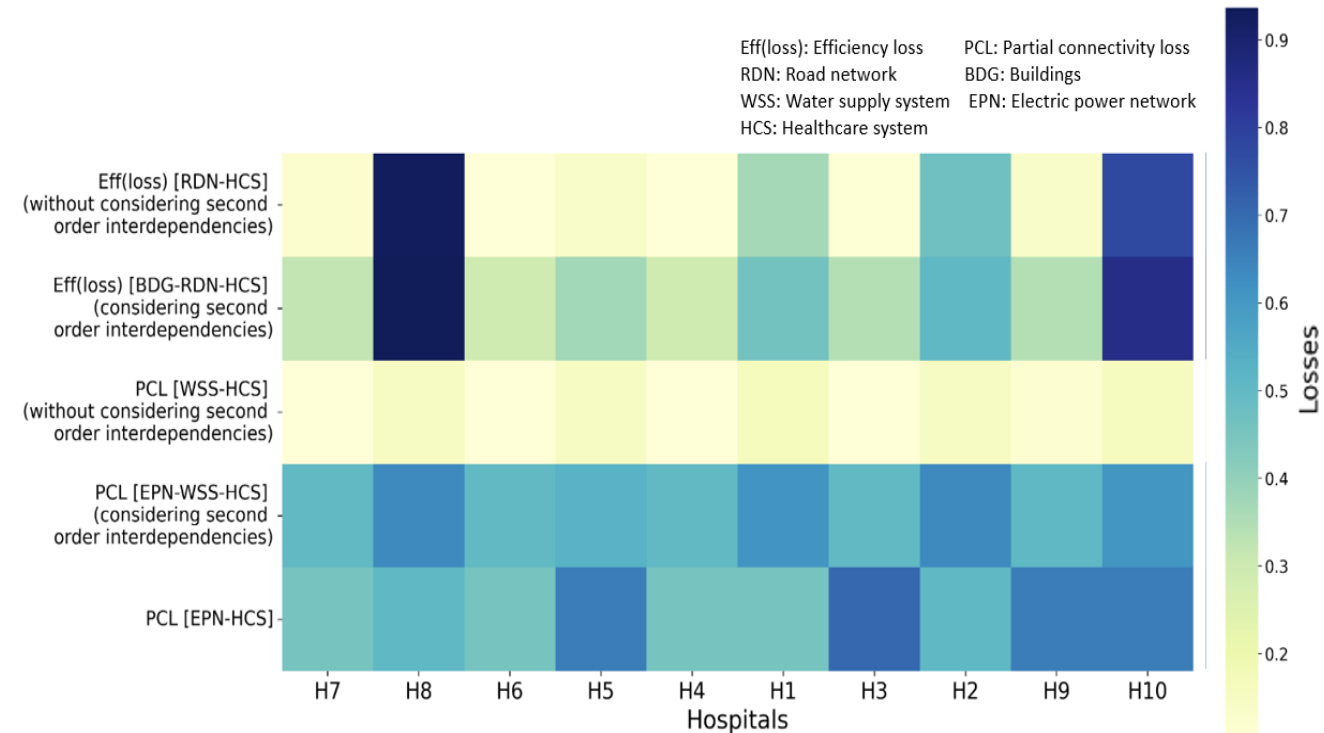
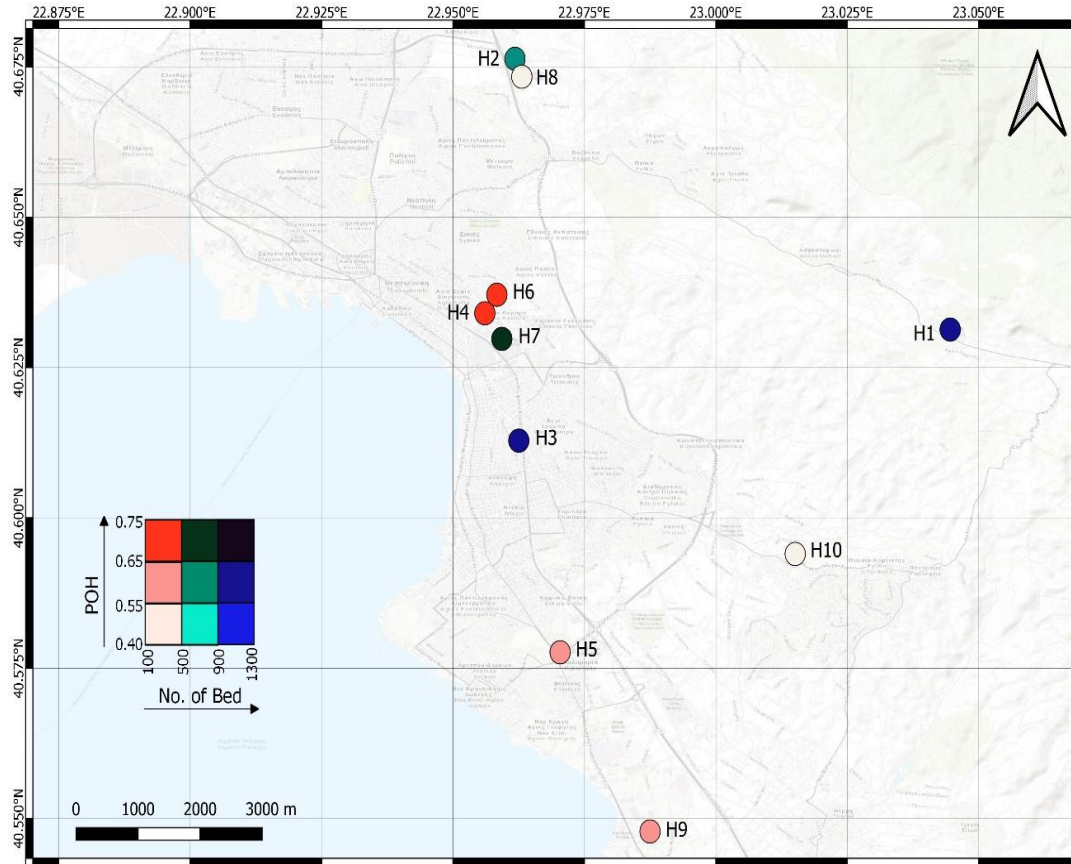


| | |
|-----------------------------|-----|
| GHT "G. Papanikolaou" | H1 |
| GHT "Papageorgiou" | H2 |
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| Inter-Balkan Medical Center | H9 |
| St. Luke's Hospital | H10 |

Impact from various external interdependent infrastructures to each hospital considering the effect of interdependencies

Systemic Seismic Risk of Critical Infrastructures at Urban Scale

Case study: Healthcare System of Thessaloniki



- Poudel, A., Argyroudis, S., Pitilakis, K., 2023. Systemic seismic risk assessment of urban healthcare system considering interdependencies to critical infrastructures. *International Journal Disaster Risk Reduction* [under review]
- Poudel, A., Pitilakis, K., Silva, V. and Rao, A., 2023. Infrastructure seismic risk assessment: an overview and integration to contemporary open tool towards global usage. *Bulletin of Earthquake Engineering*, pp.1-26

Thank you