# 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

**Kyriazis Pitilakis, Evi Riga & Stefania Apostolaki (AUTH)**
**Nicosia, 08/02/2024**

# 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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# SERA European Research Programme

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

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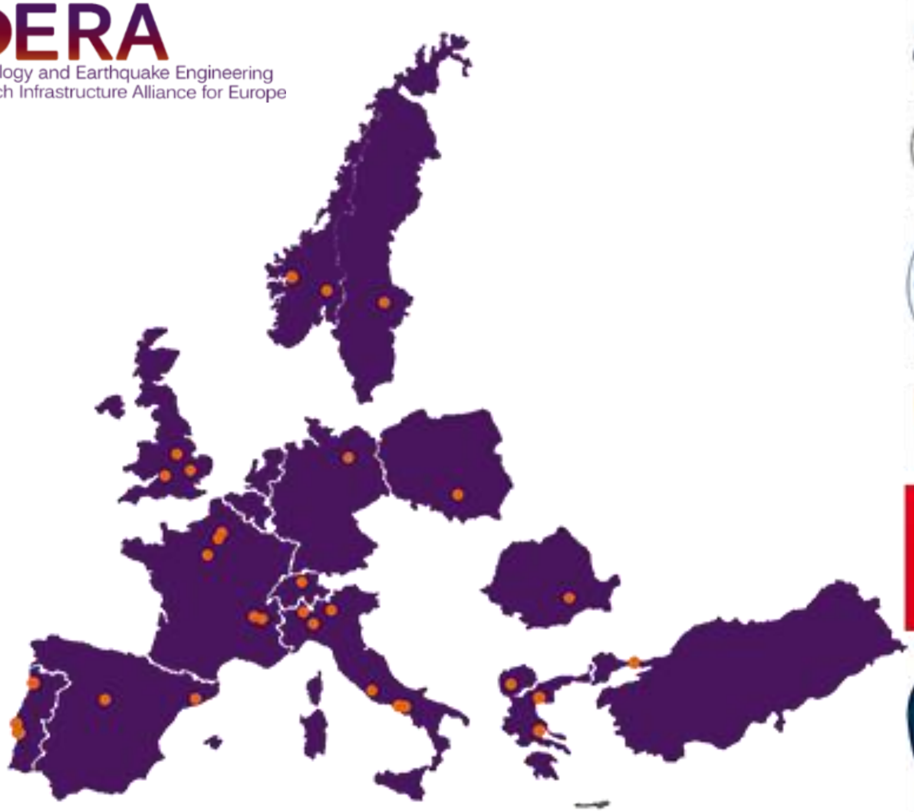

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# The European Seismic Hazard Model ESHM20

- 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. Wheatherill, F. Cotton GFZ Seismic Hazard and Risk Dynamics*

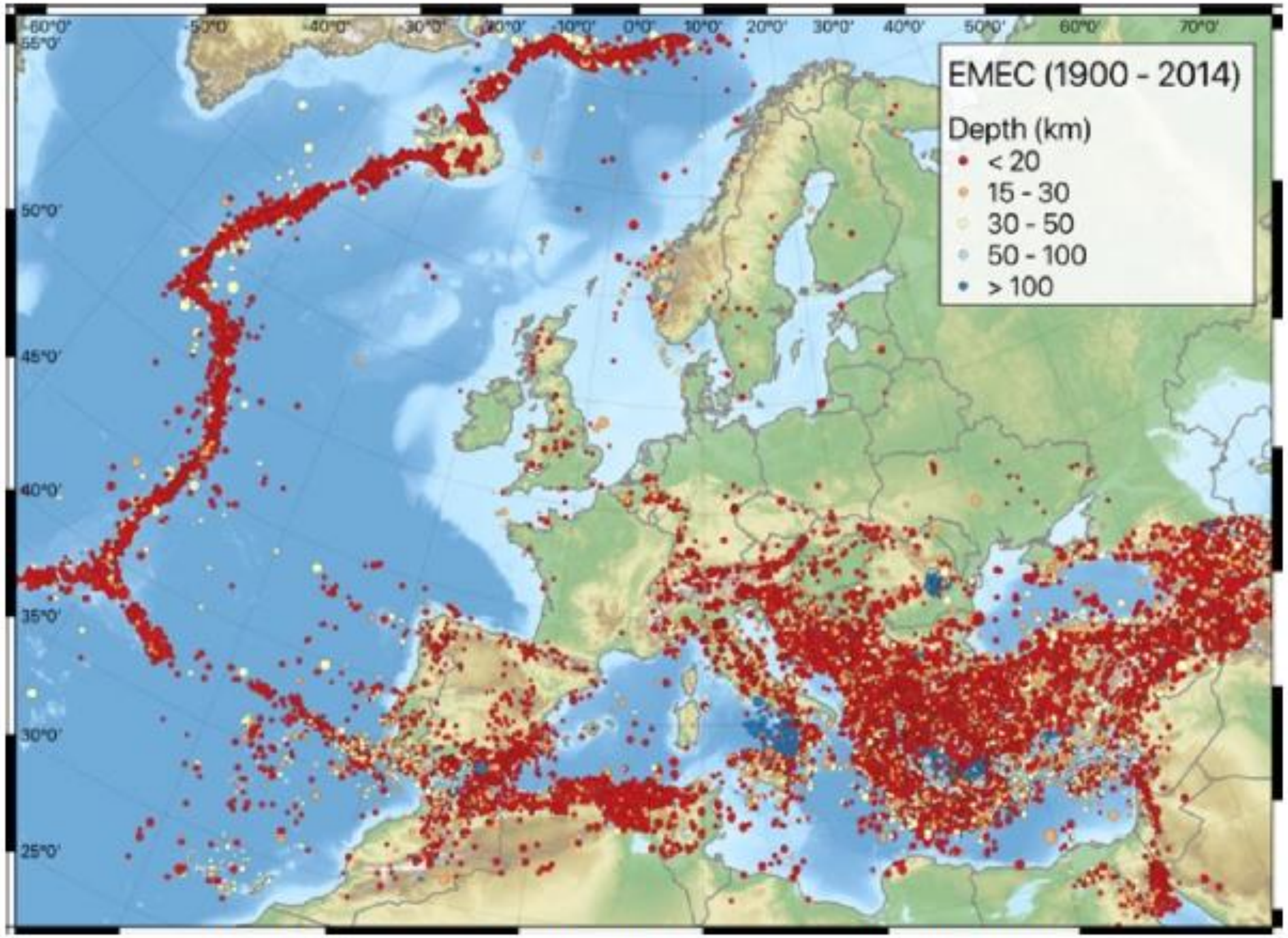


**Fig. 1.4** The complete EMEC catalogue for the period 1900 – 2012.

# Main results of ESHM20

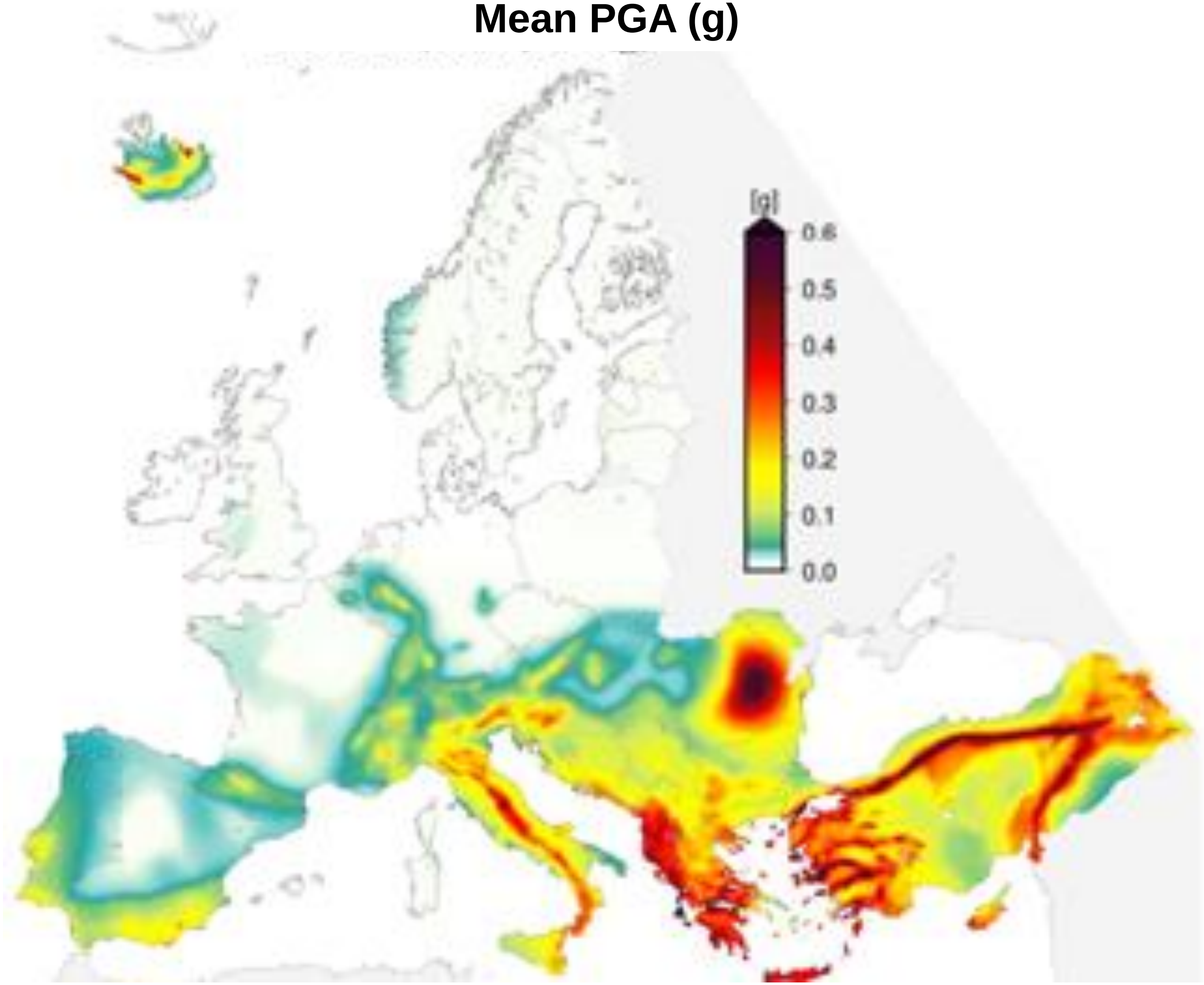
The ESHM20 results depict time-independent earthquake ground-shaking exceedance levels for a uniform **rock site condition of $V_{s,30} \geq 800$ m/s**.

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](hazard.EFEHR.org)**

# Indicative results of ESHM20

Hazard map:
**Mean PGA (g)**



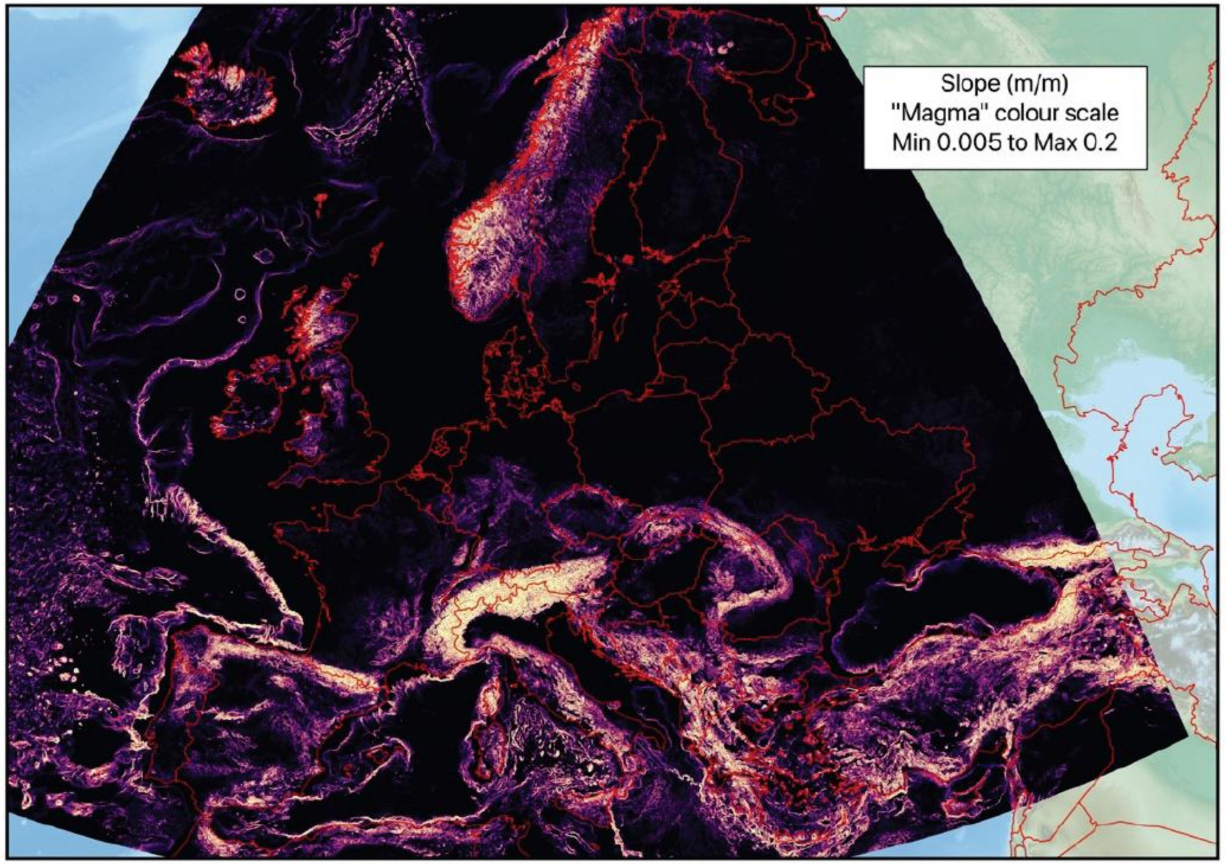
# The European Seismic Risk Model ESRM20

**Main features:**

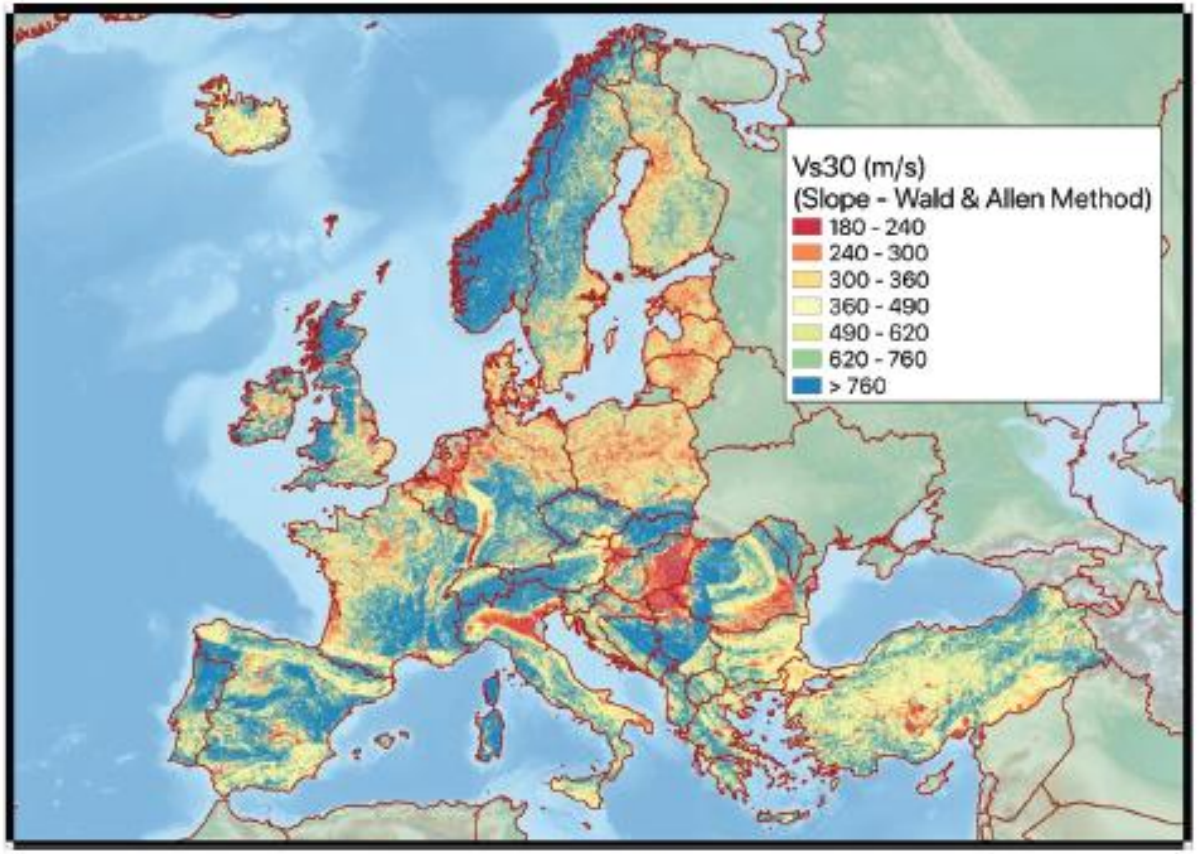
- ☐ **European Seismic Hazard Model 2020 (ESHM20)**: Seismogenic source model and ground motion model logic trees
- ☐ **European Site Amplification Model**: European model of proxy site data (geological era and topography) serving as input variables to the ground motion models
- ☐ **European Exposure 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)

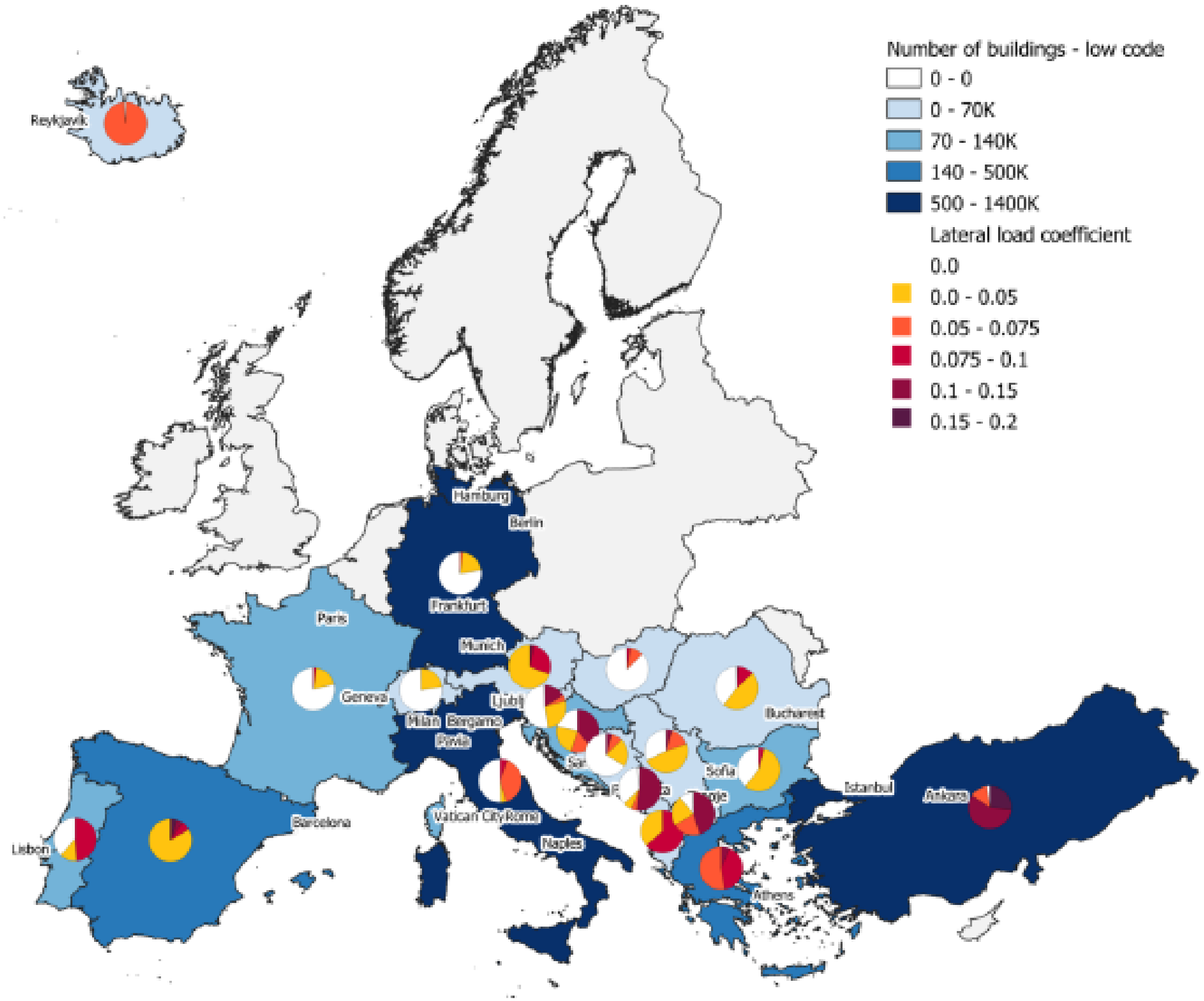


Vs30 inferred from GEBCO topography/bathymetry using the Wald and Allen (2007) correlation approach

*Weatherill et al. (2020)*

# 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/esrm20_exposure

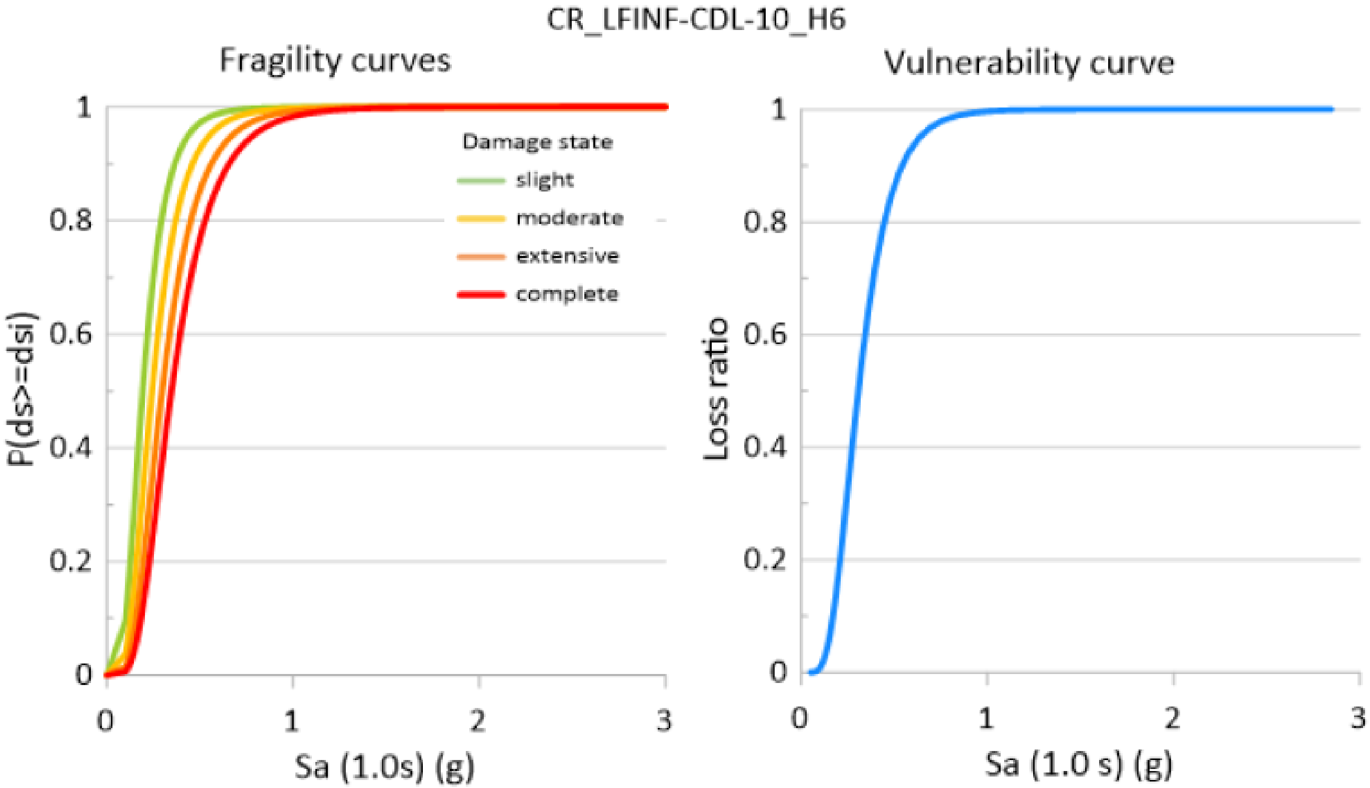


*Crowley et al. (2021)*

# 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.



*Romão et al., (2021)*

# ESRM20 Indicative Outputs

## Average Annual Economic Loss

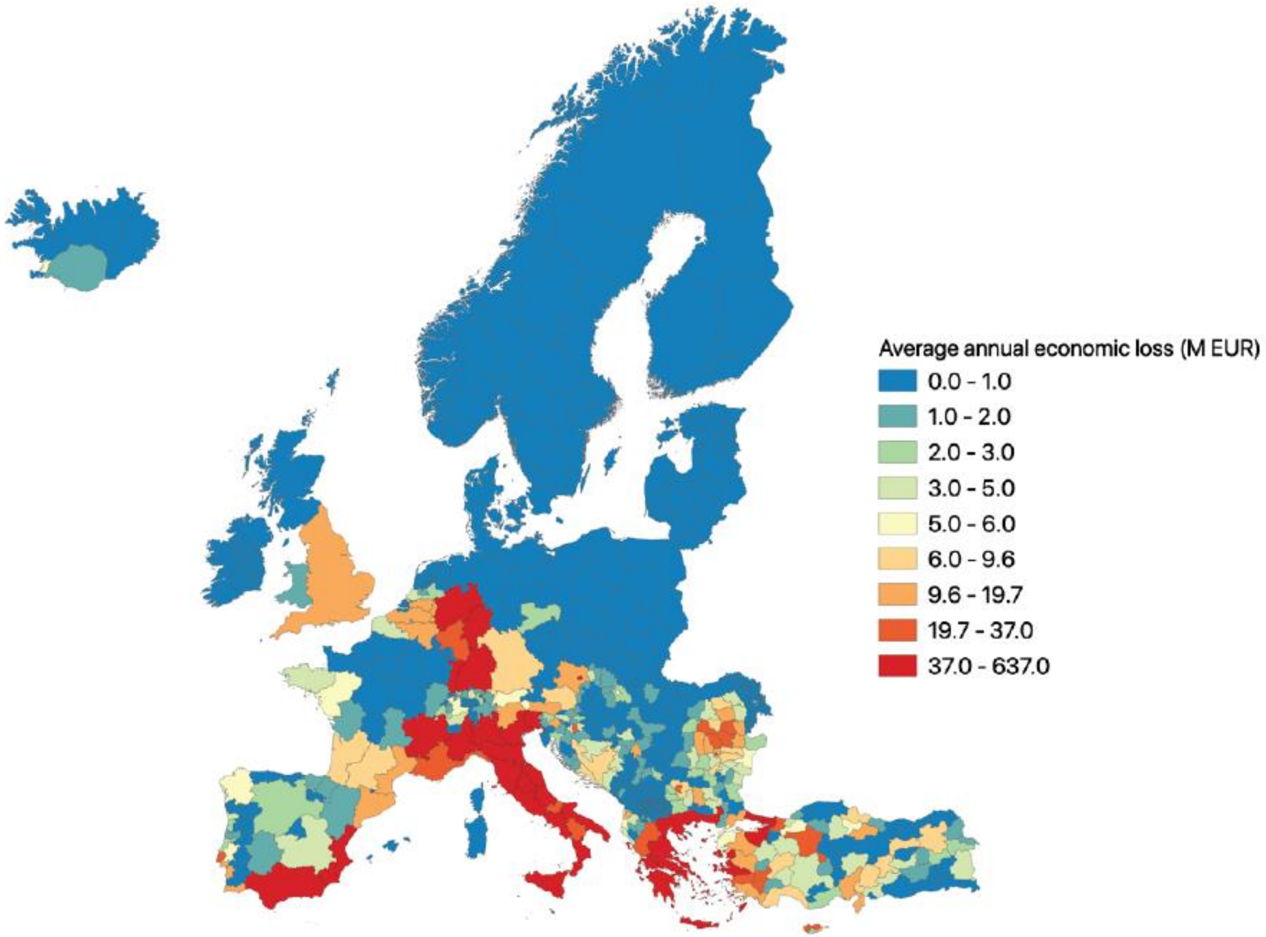


**Fig. 6.3** Map of the average annual economic loss across Europe at administrative level 1

## Average Annual Loss of Life

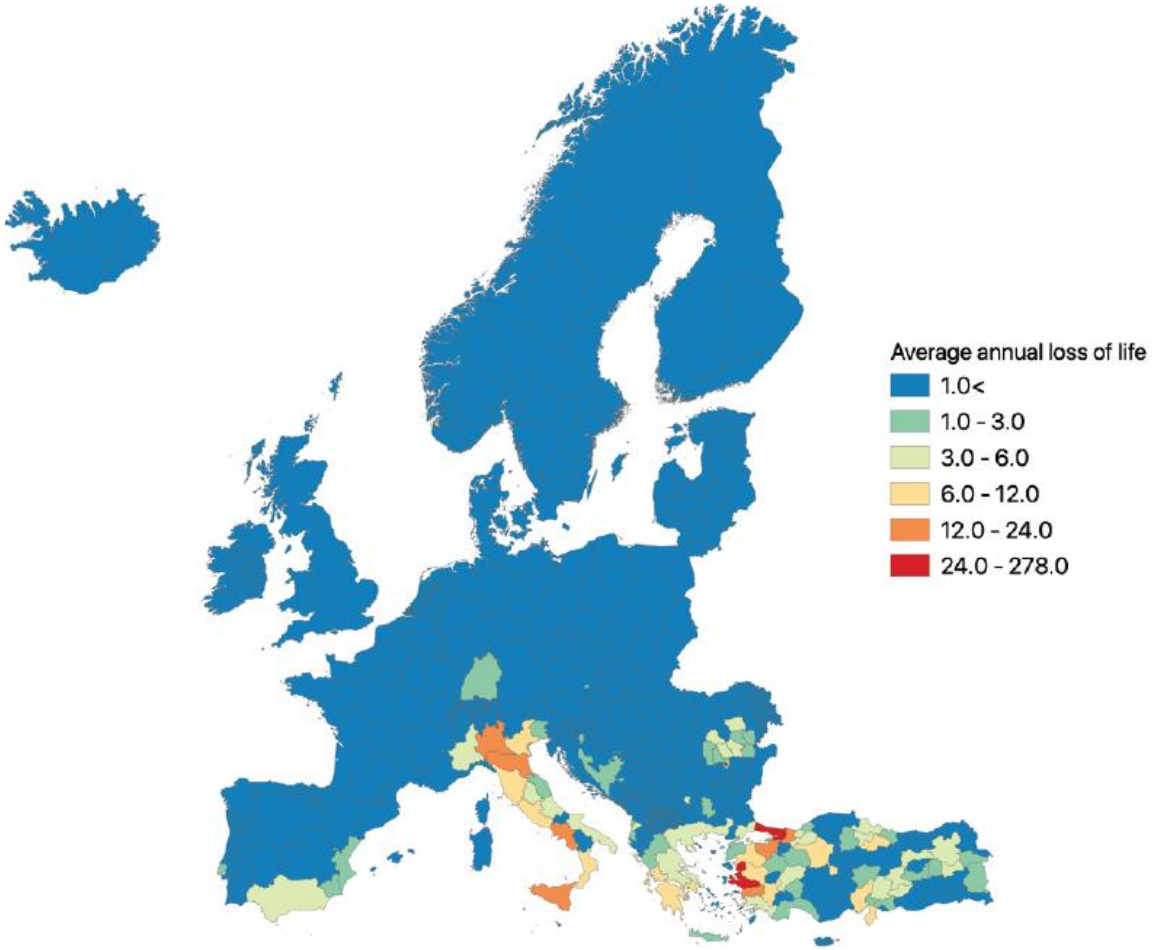


**Fig. 6.5** Map of the average annual loss of life across Europe at administrative level 1

*Crowley et al. (2021)*

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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

**$S_\alpha$**: maximum spectral acceleration (for 5% damping) corresponding to the constant acceleration branch of the horizontal elastic response spectrum

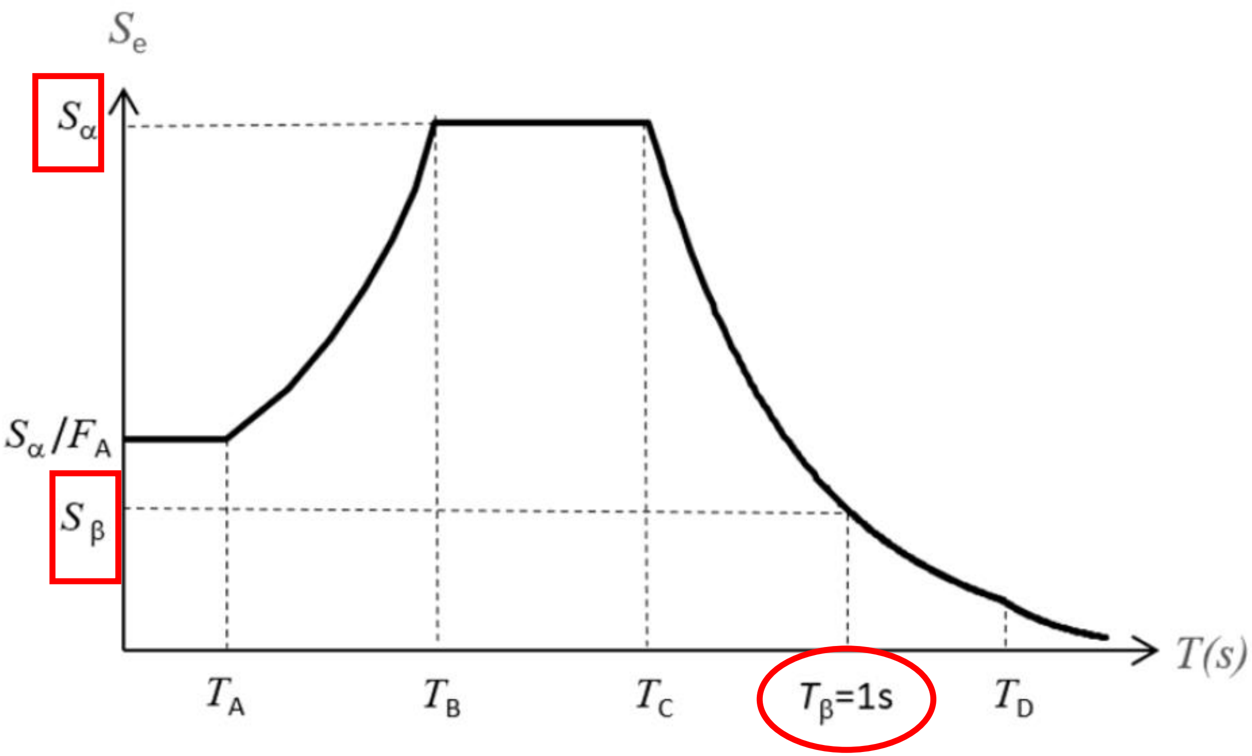
**$S_\beta$**: spectral acceleration (for 5% damping) of the horizontal elastic response spectrum corresponding to an vibration period $T_\beta$=1.0s

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

**$F_\alpha$**: soil amplification factor applied to the $S_\alpha$

**$F_\beta$**: soil amplification factor applied to the $S_\beta$

**$F_T$**: topography amplification factor

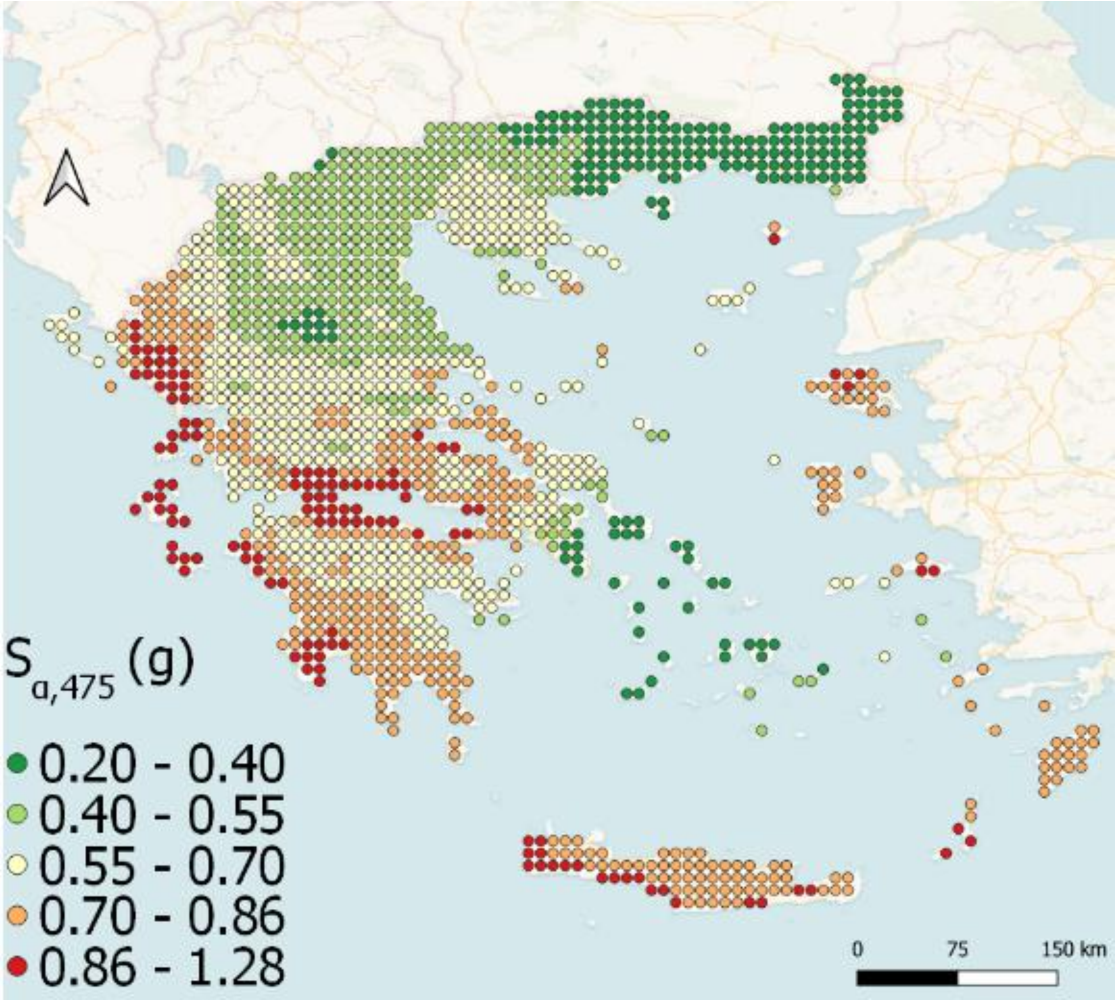


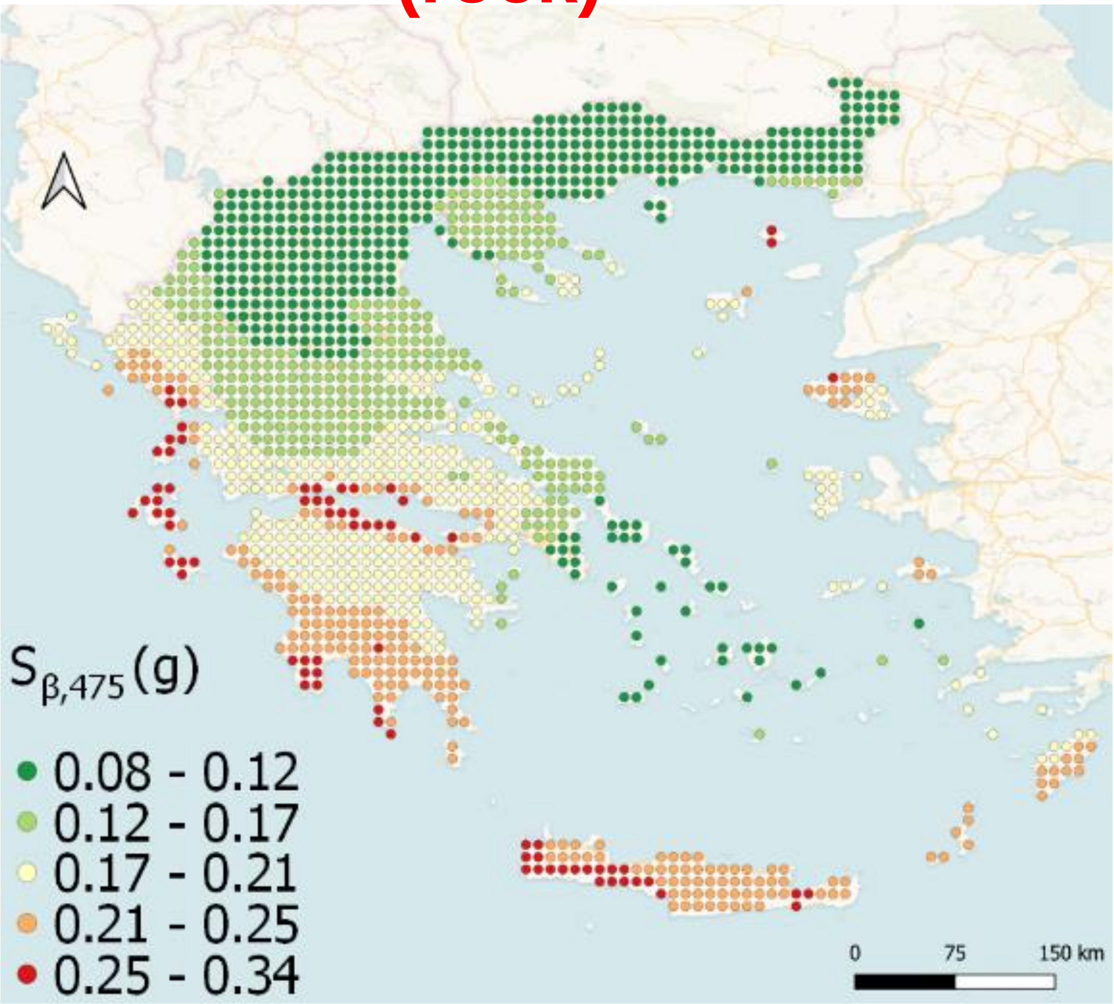
$$T_C = \frac{S_\beta T_\beta}{S_\alpha}$$

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

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

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





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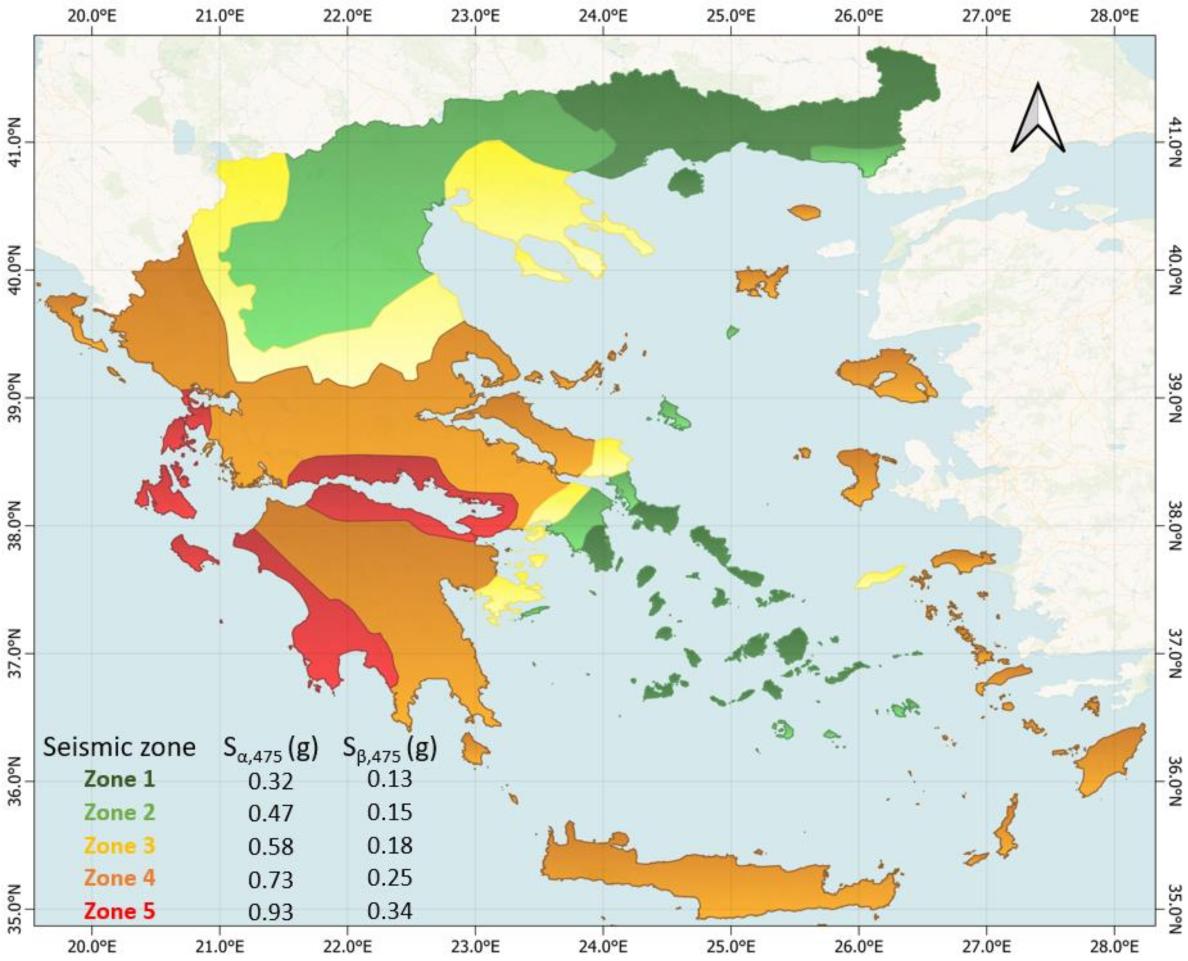
# Seismic hazard map for Greece

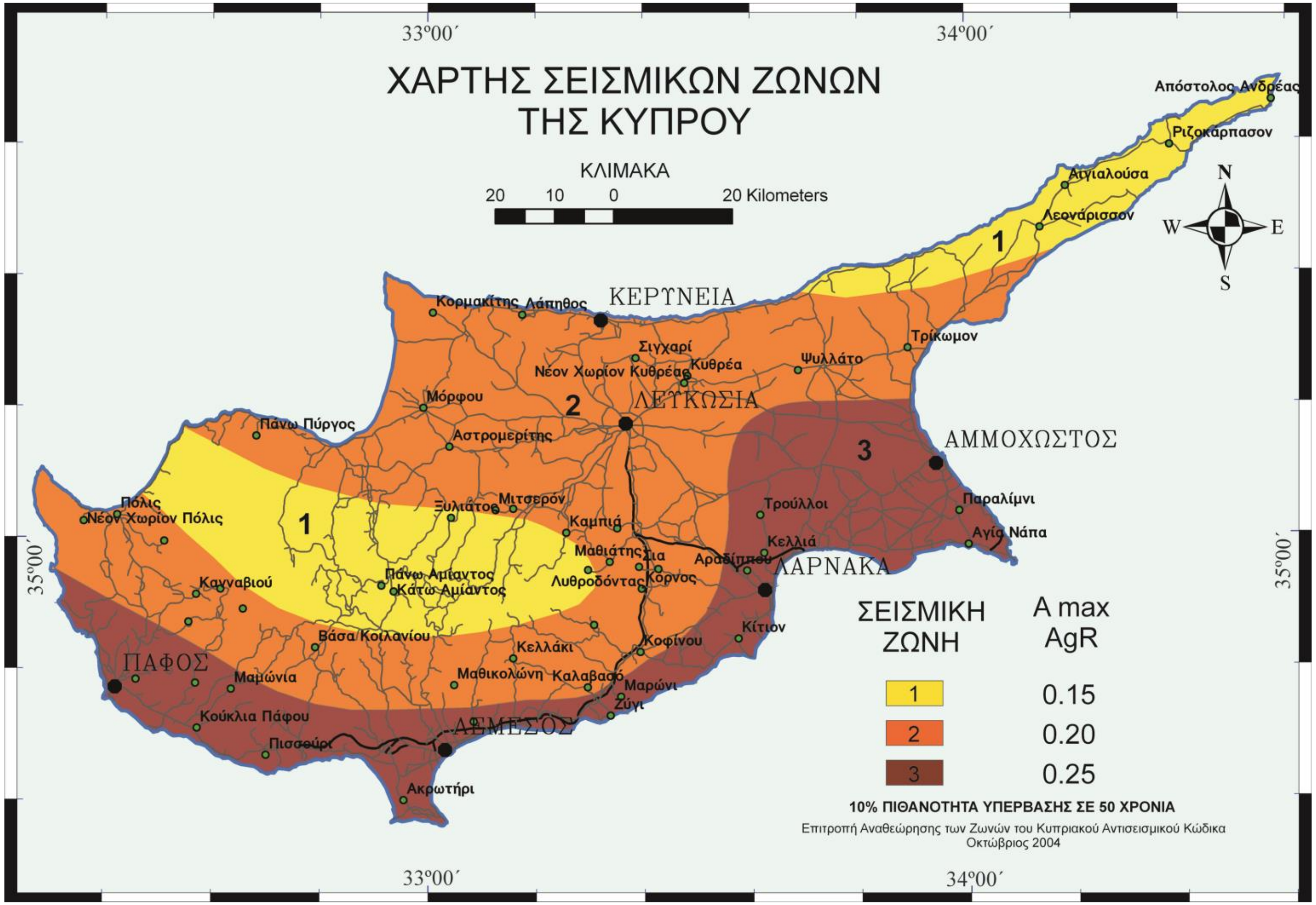


## Proposed seismic hazard map for rock conditions ($V_s$>800 m/s)

| 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** | 0.0 | 0.09 | 0.35 | 3.45 |

*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



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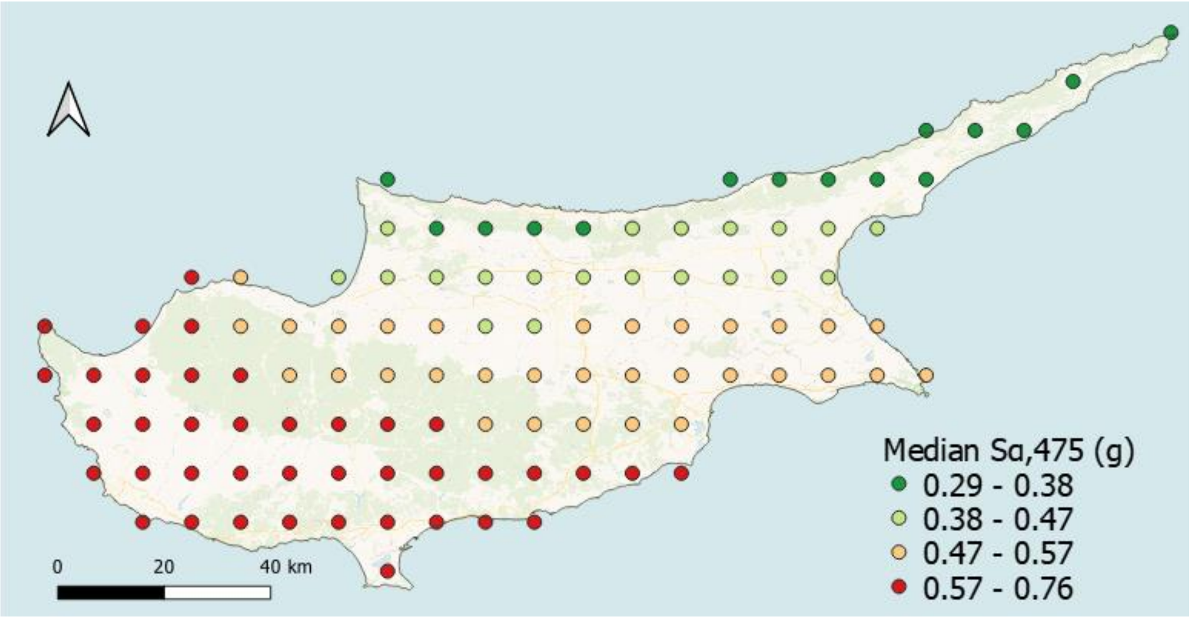
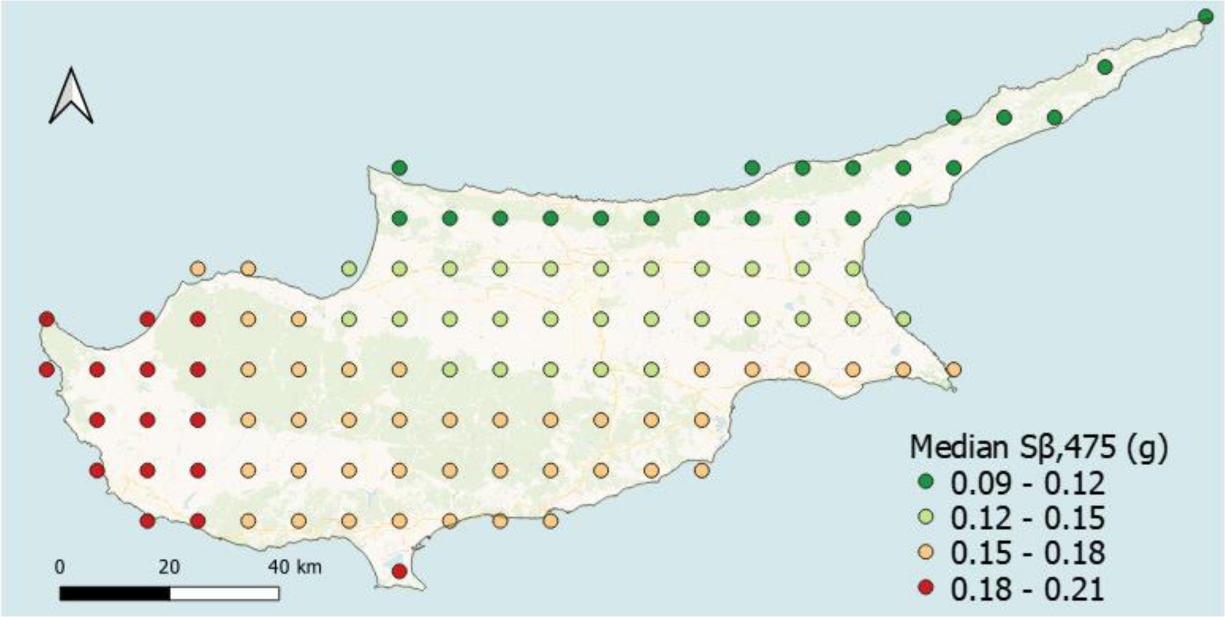
# Development of the seismic hazard map for Cyprus

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.

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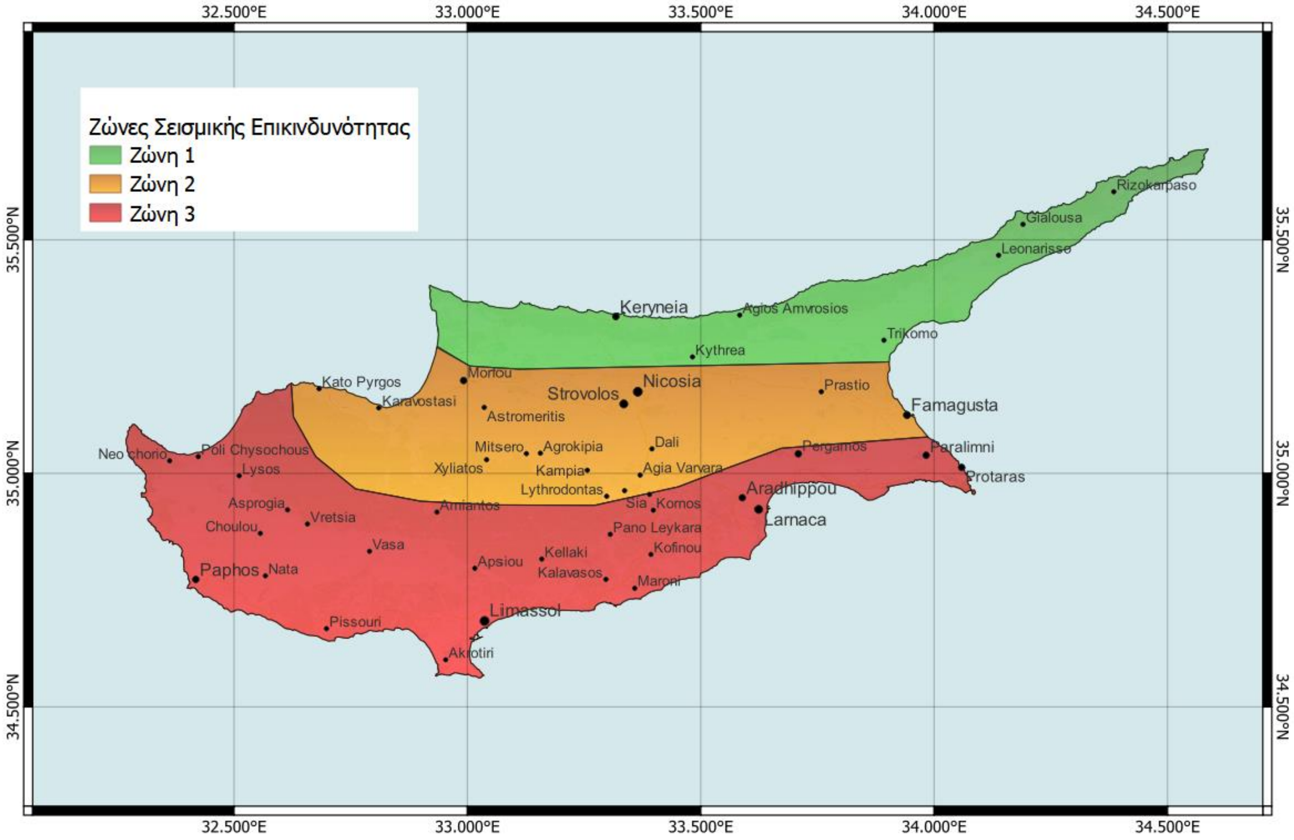
# Proposed seismic hazard map for Cyprus

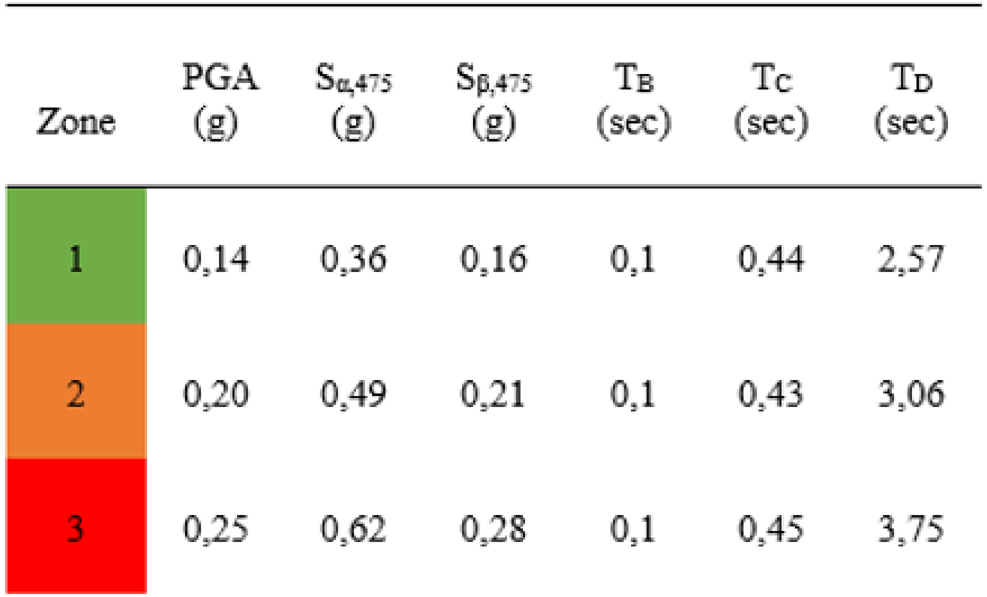
- **Step 2:** Calculation of the ratio of the proposed zone-based PGA to the PGA from the nearest point of the ESHM20 canvas + population criteria

| 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) | $S_{\alpha,475}$ (g) | $S_{\beta,475}$ (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., Πιτιλάκης, Κ., Πιτιλάκης, 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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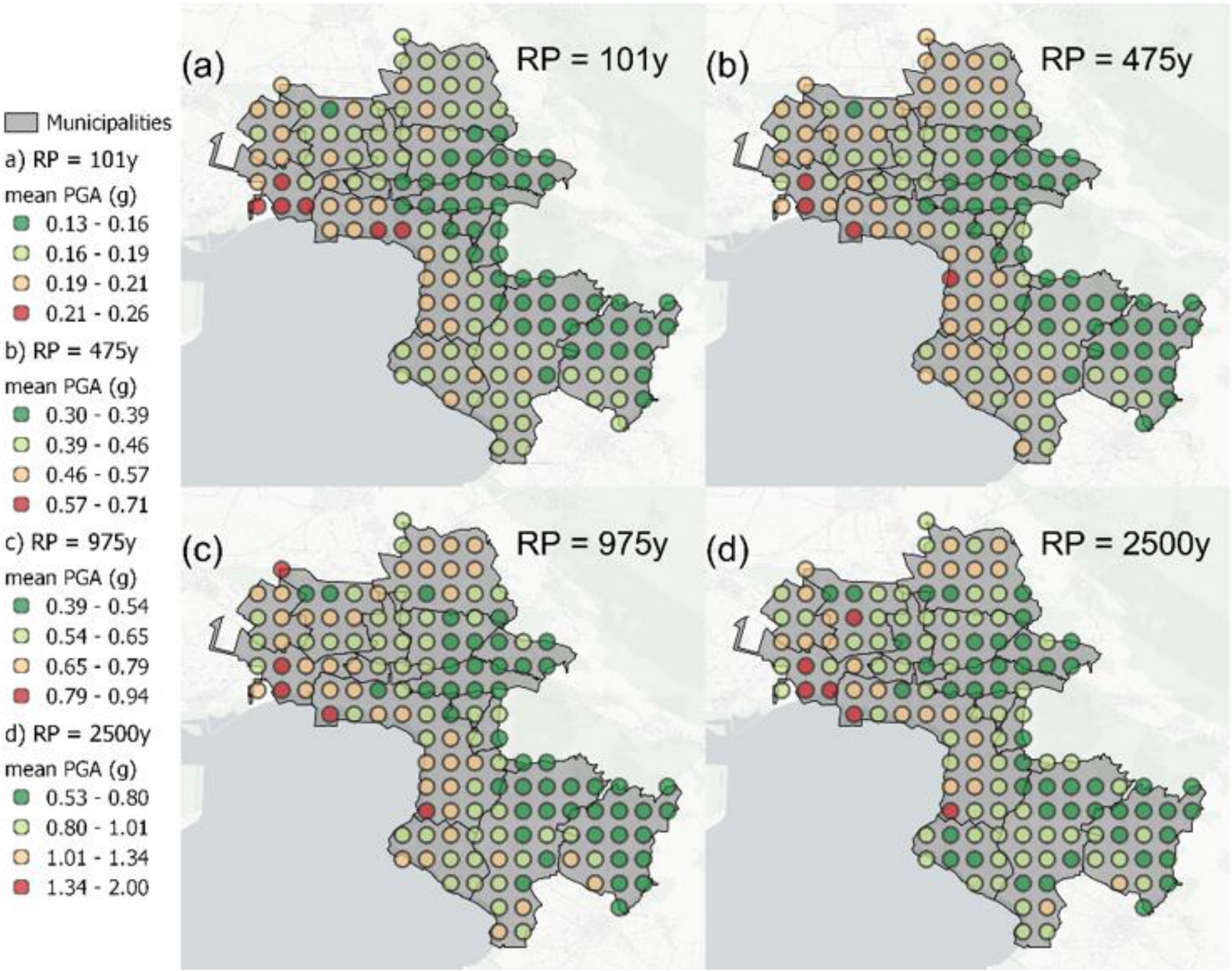
# Probabilistic seismic hazard and risk assessment for Thessaloniki, Greece

- 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

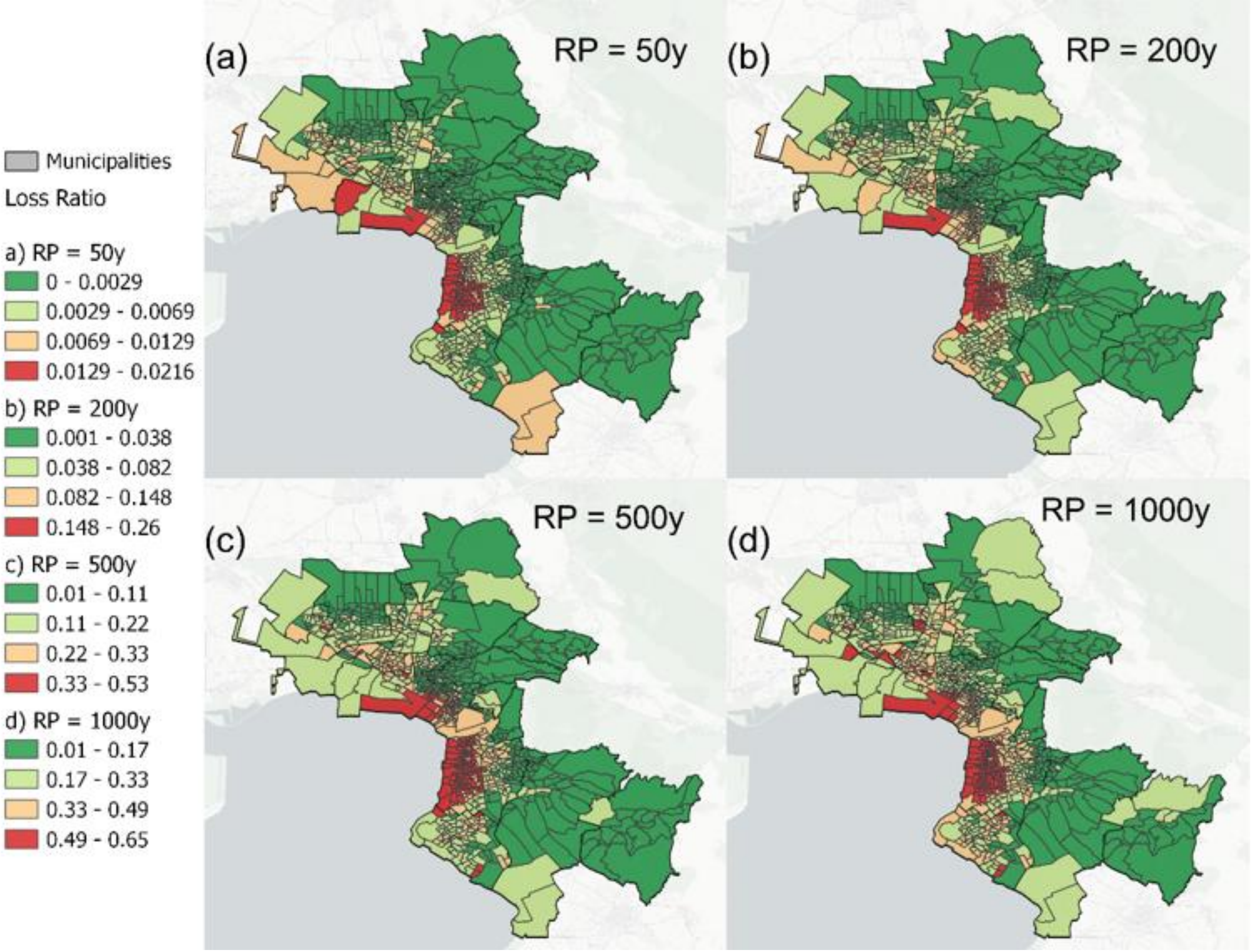
*Apostolaki S, Riga E, Pitilakis D. (2022). Probabilistic seismic hazard and risk assessment of Thessaloniki, Greece. 3rd European Conference on Earthquake Engineering & Seismology. 4-9 September, Bucharest, Romania.*

# Results of the PSHA analysis



# Results of the Stochastic Event-based Risk analysis

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



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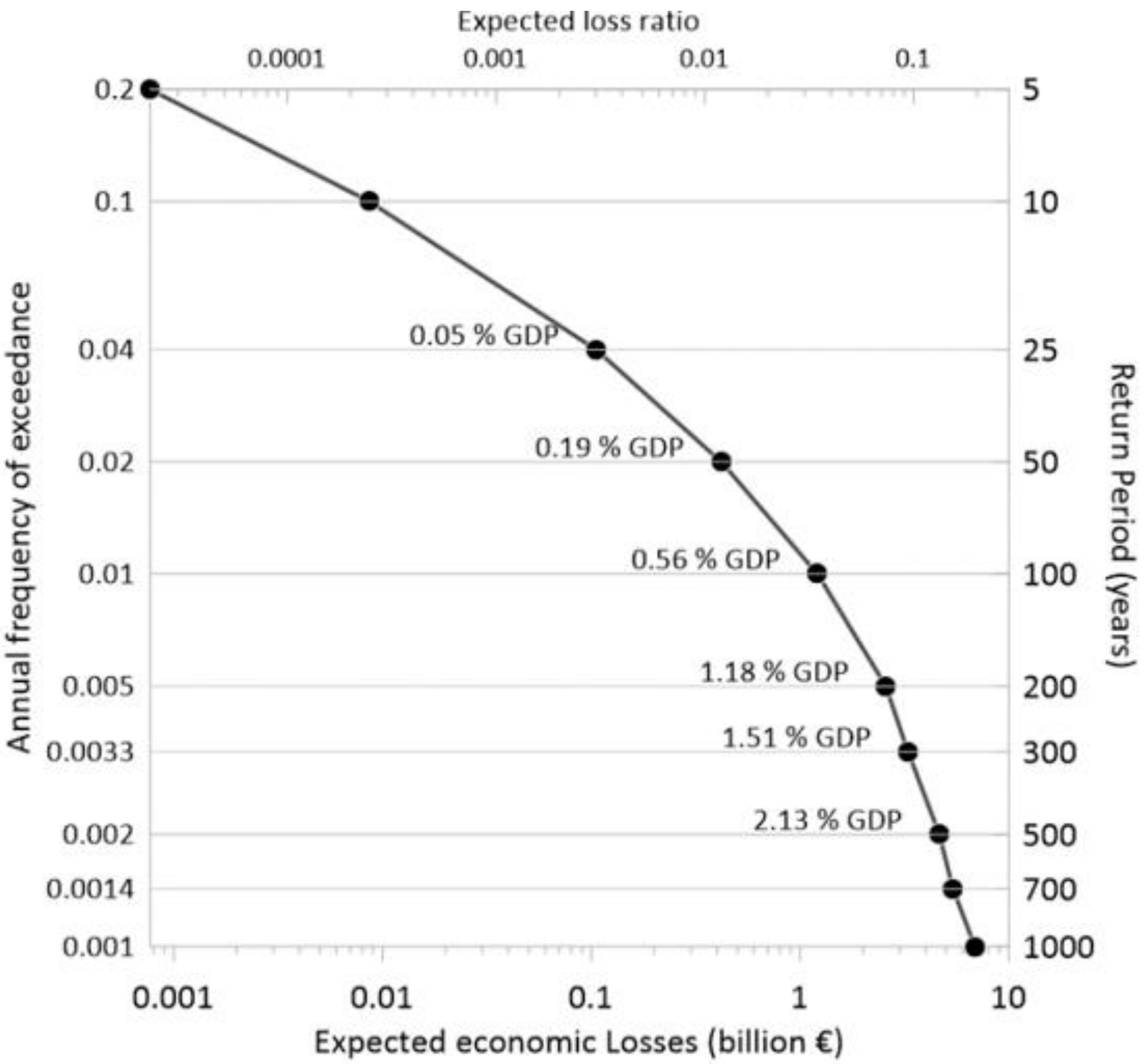
# Loss exceedance curve for Thessaloniki

GDP = 217.7 billion €



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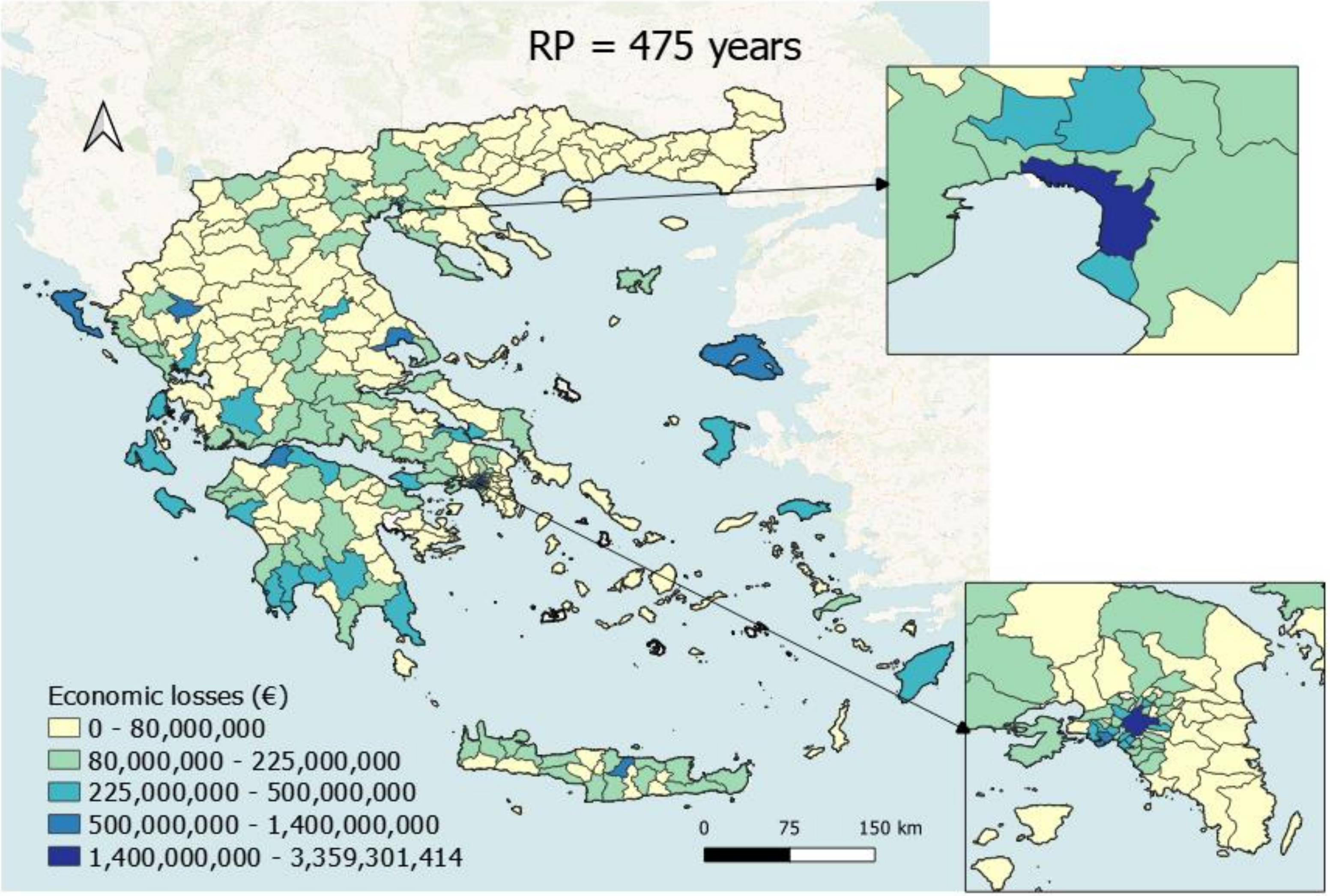
# Risk assessment at national level (Greece)

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**

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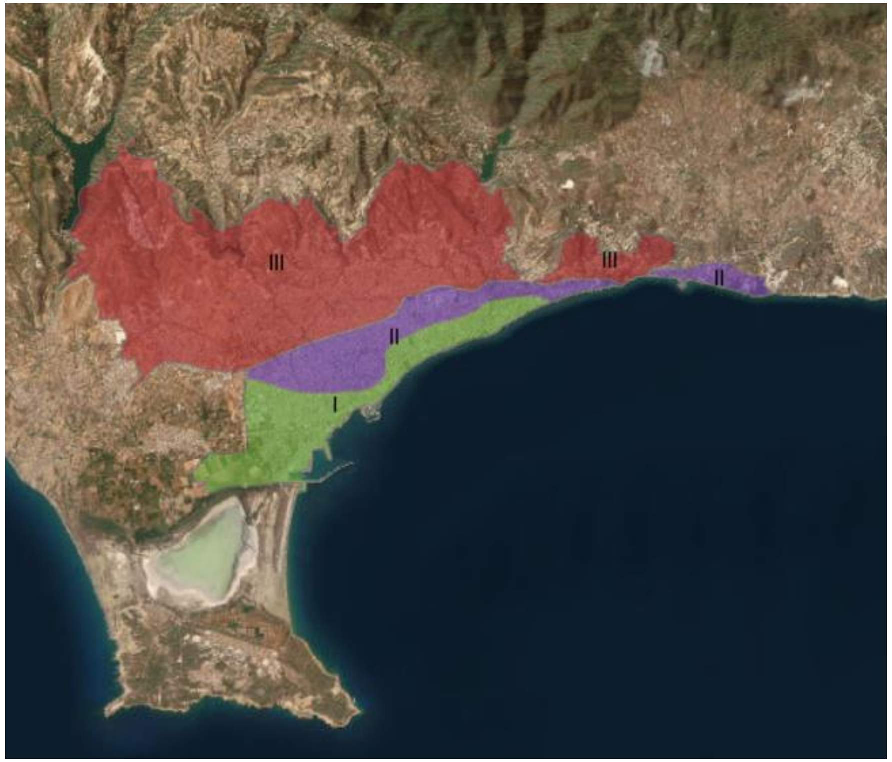
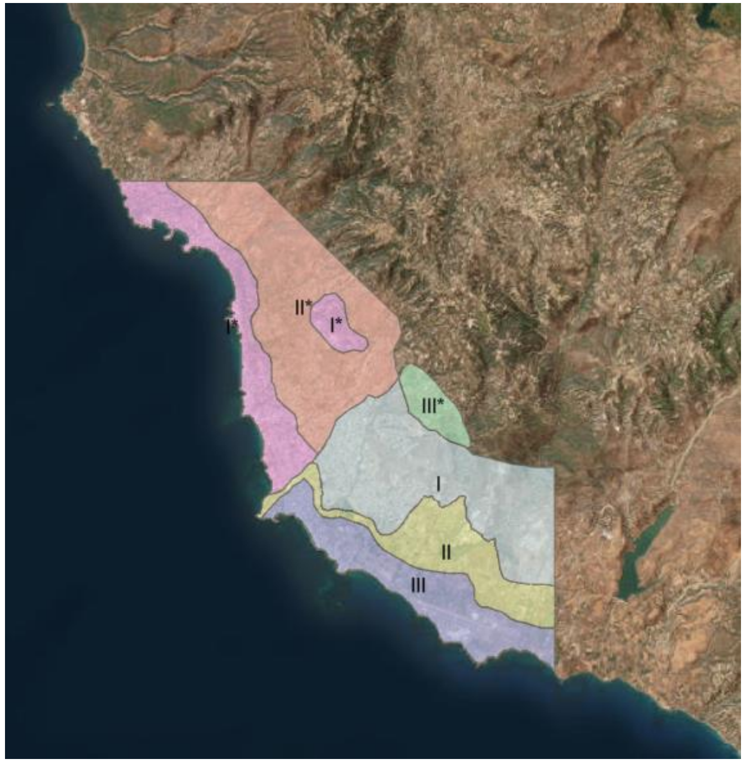
# Microzonation studies in Cyprus

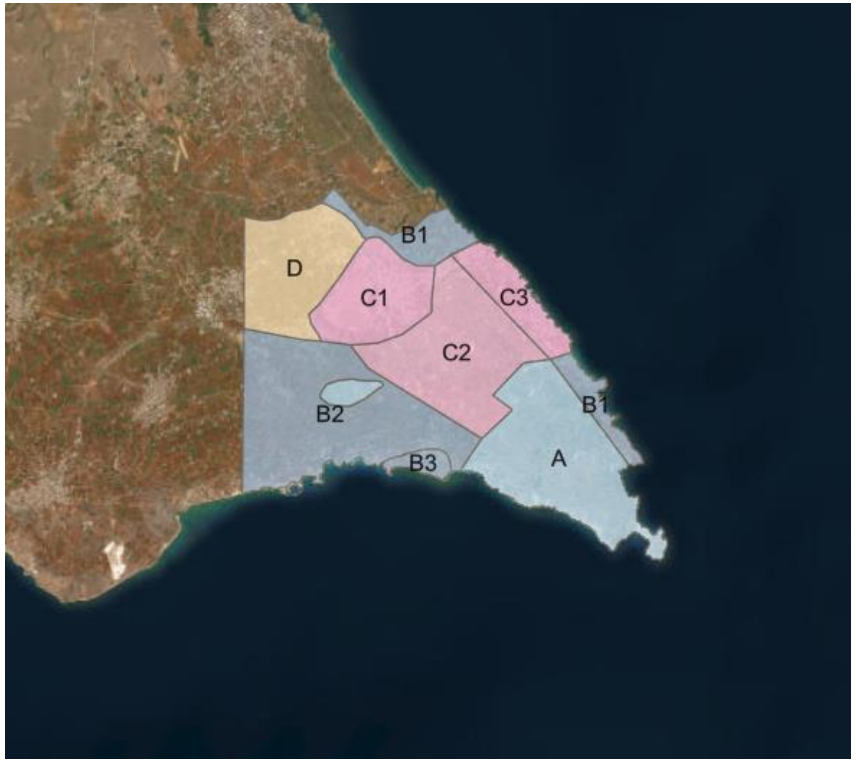
## Limassol (2000)



## Paphos (2005)



## Ammochostos (2020)

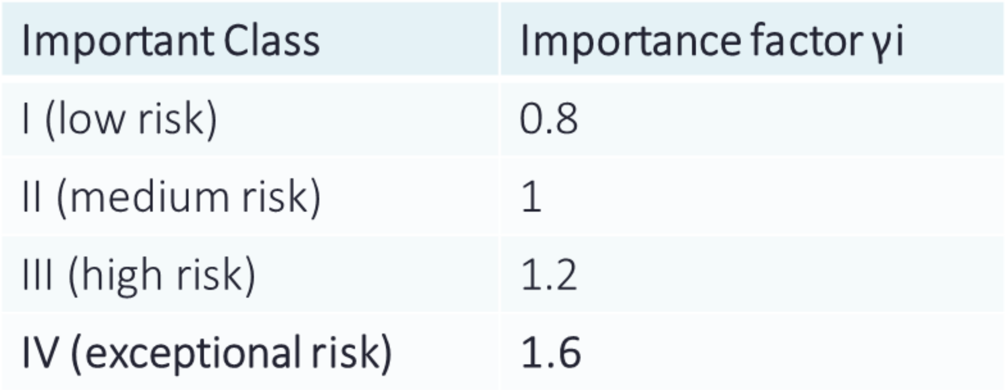


GEOportal of Cyprus Geological Survey Department
https://geoportal-gsd.moa.gov.cy/portal/apps/

# Seismic demand for industrial facilities in the Eurocodes

## Current EC8 – Part 4

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



| Important Class | Importance factor γi |
|---|---|
| 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).

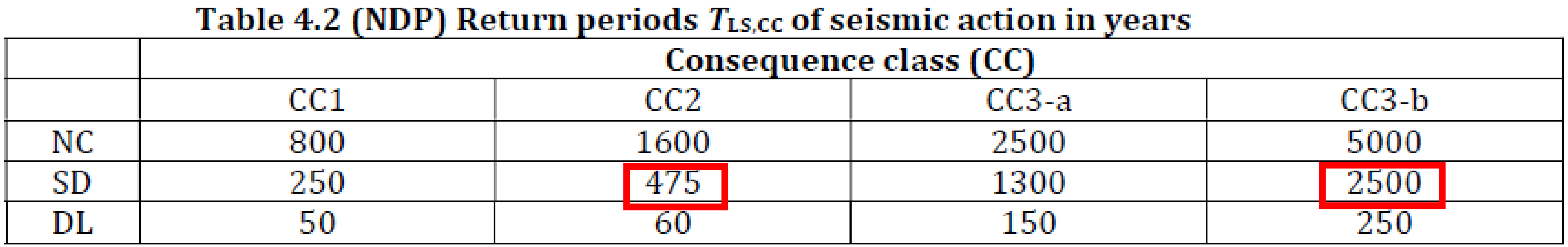


**Table 4.2 (NDP) Return periods $T_{LS,CC}$ of seismic action in years**

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

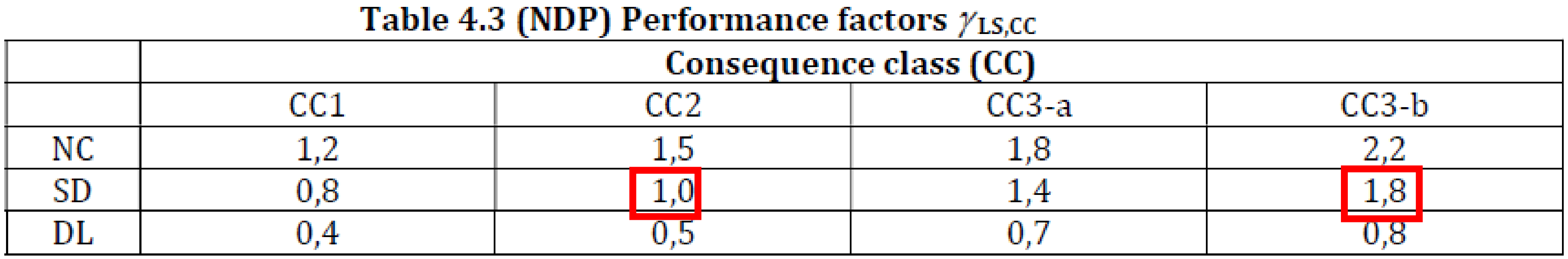
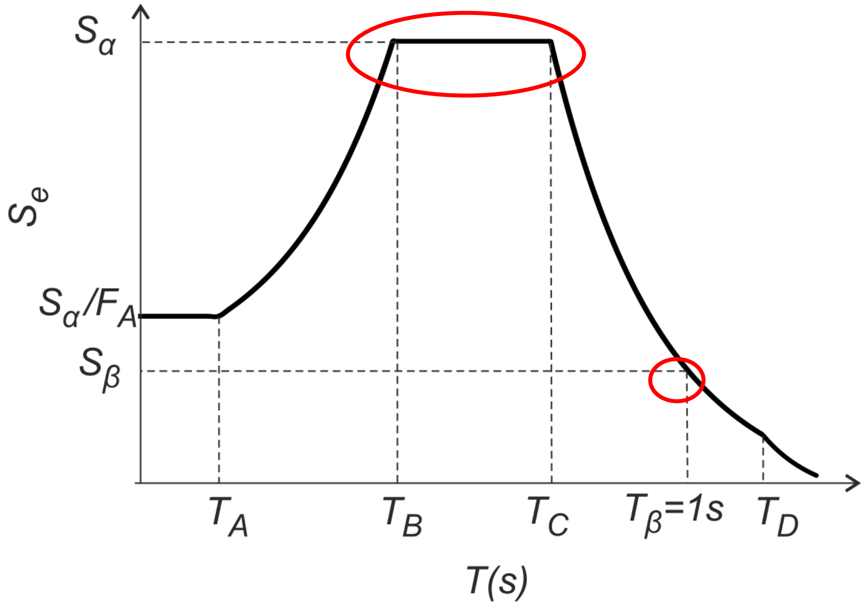


**Table 4.3 (NDP) Performance factors $\gamma_{LS,CC}$**

| | 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*

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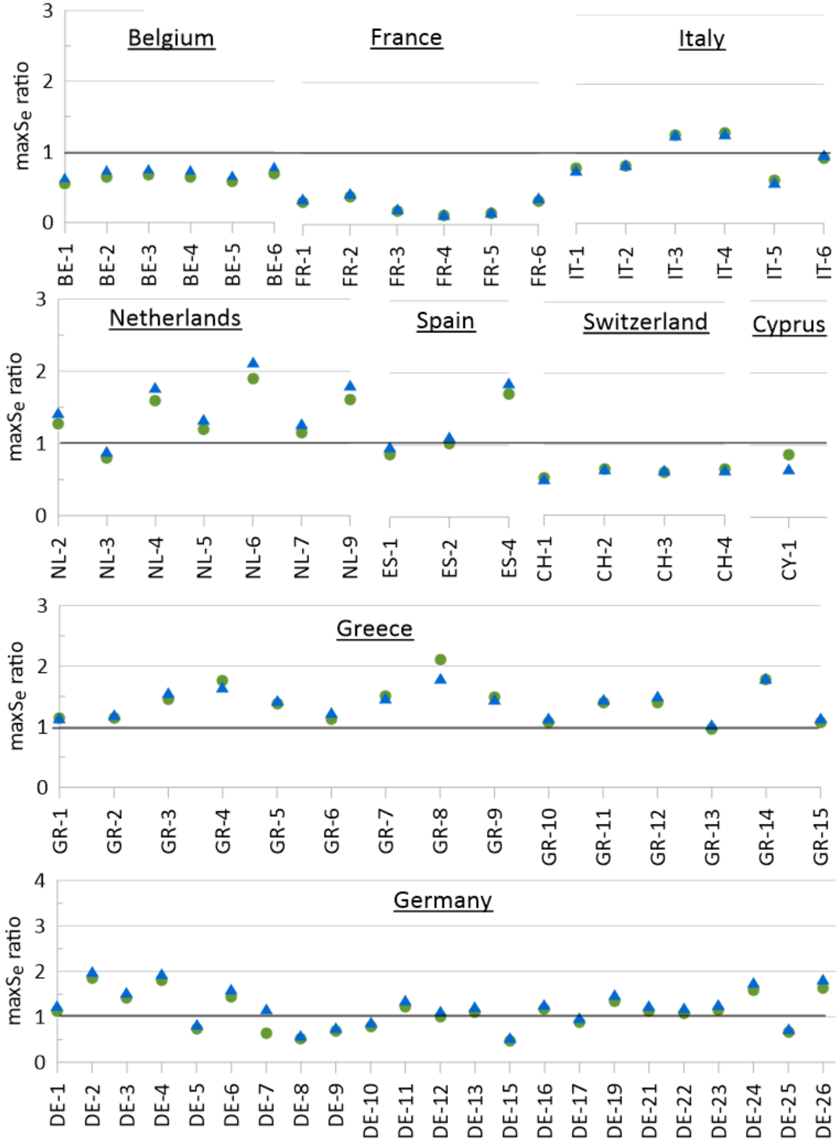
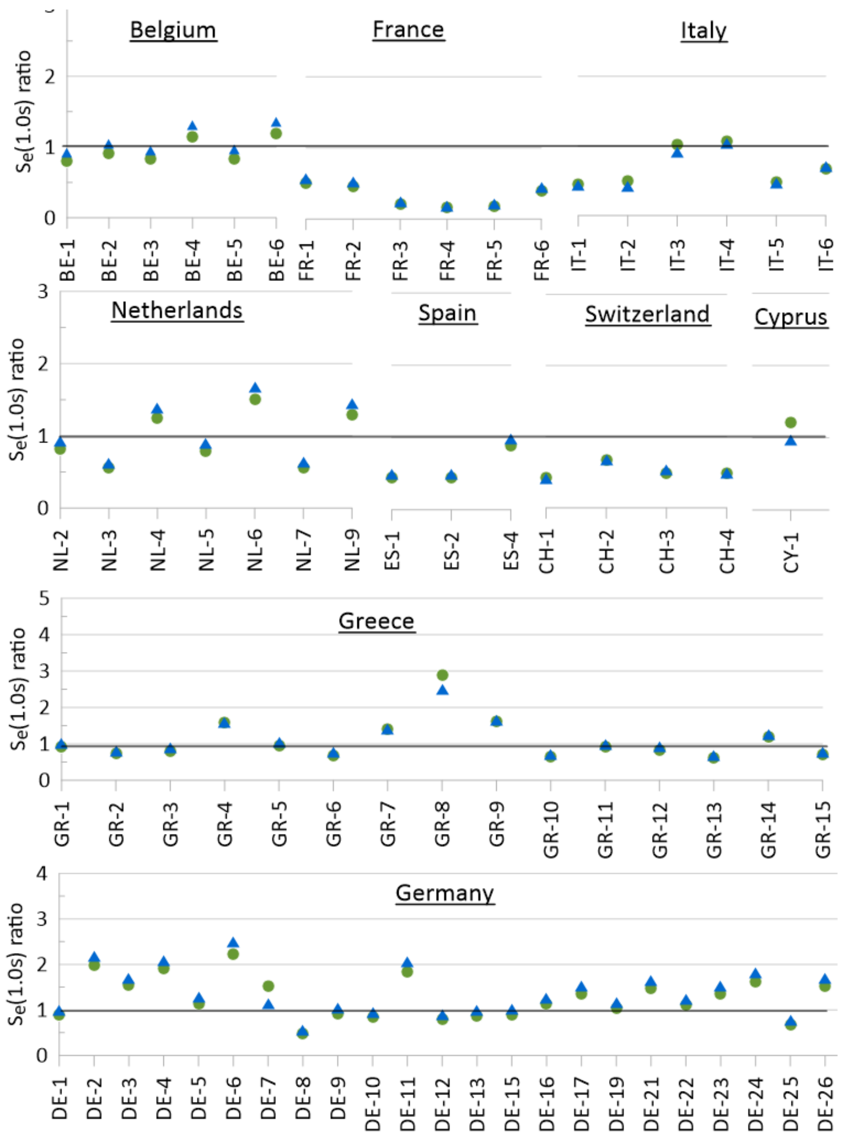
# Implication of the ESHM20 to the seismic design of industrial facilities



$S_\alpha$-Approach2 / $S_\alpha$-Approach 1 ● 475y ▲ 2500y

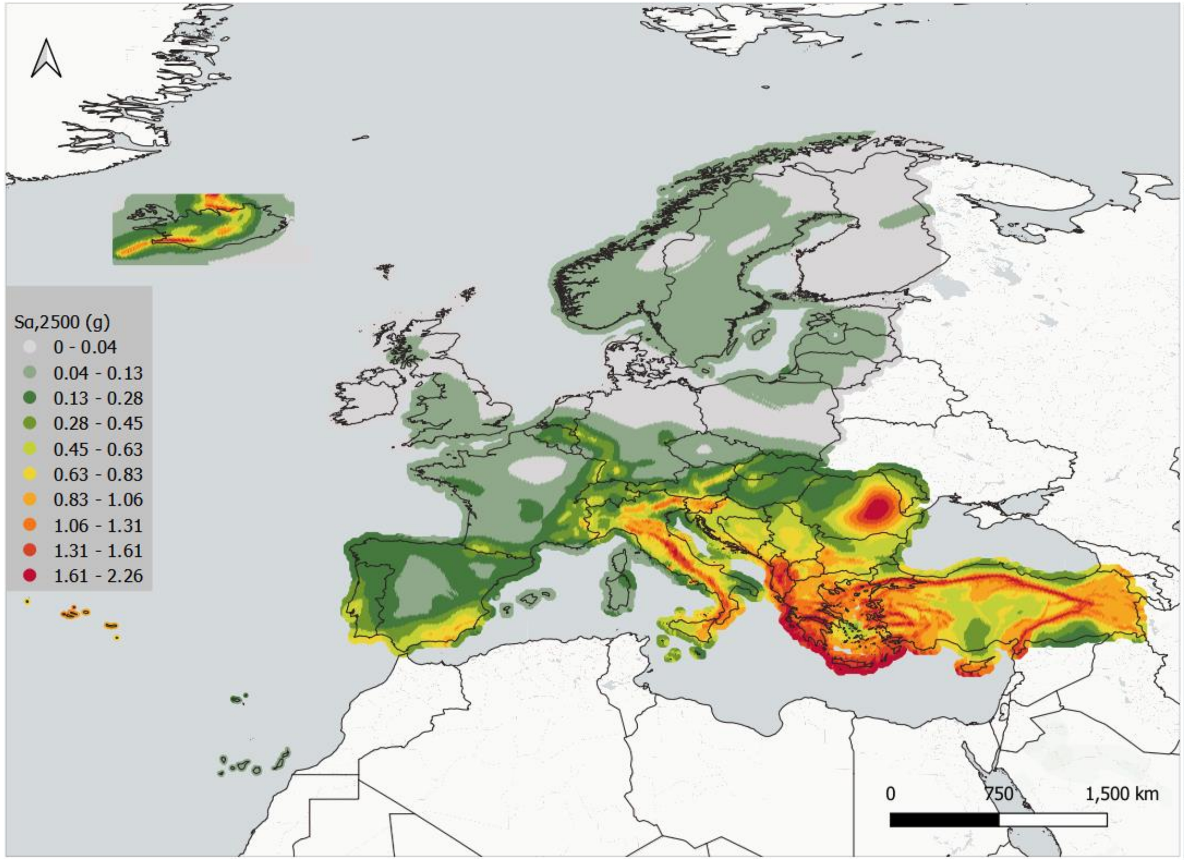


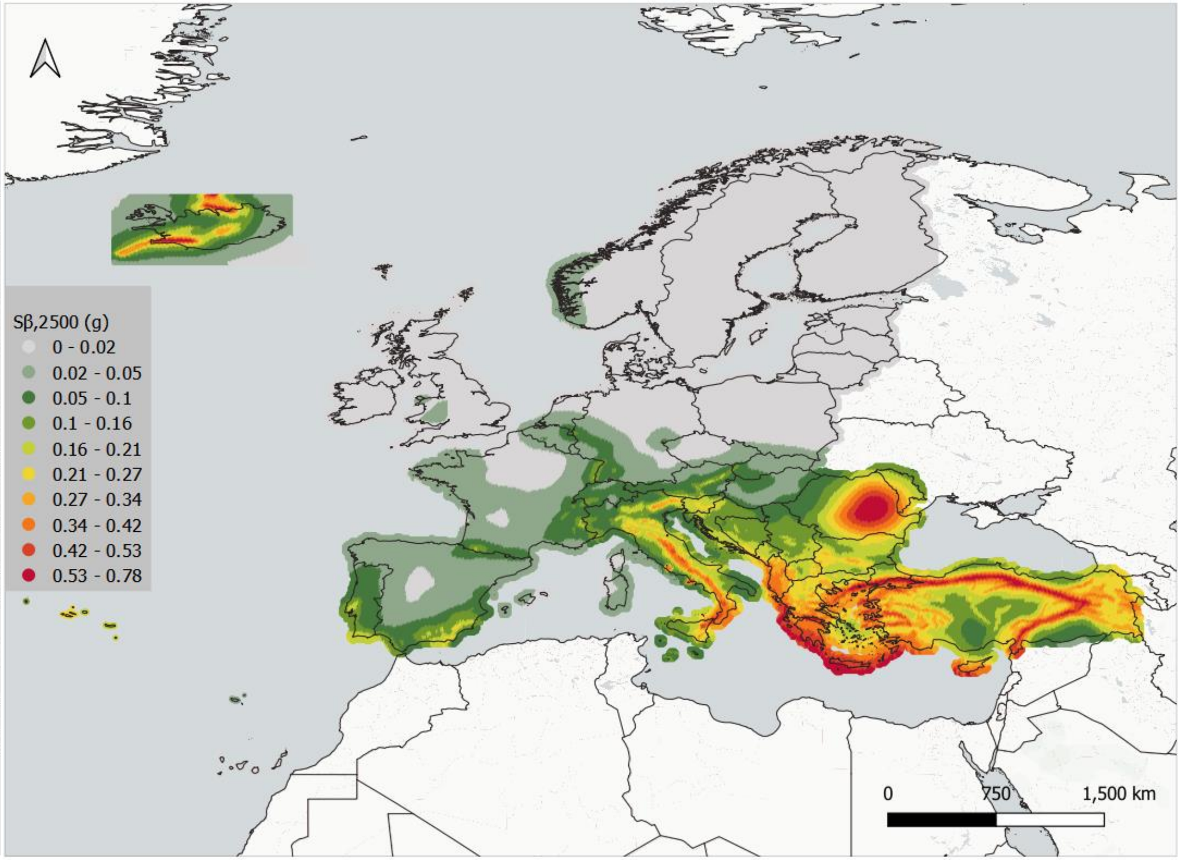
$S_\beta$-Approach2 / $S_\beta$-Approach 1 ● 475y ▲ 2500y

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

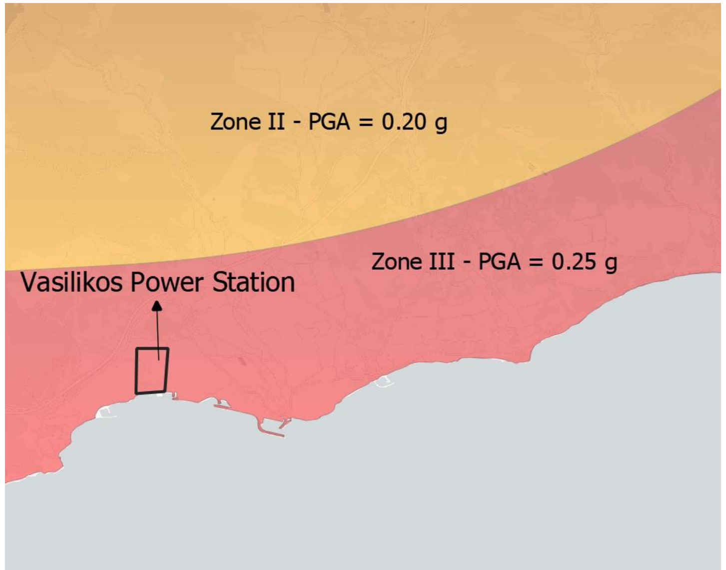
APPLICATION → a hypothetical steel Storage Tank at the Vasilikos Power Station

**SEISMIC DESIGN (2500 years return period) →**

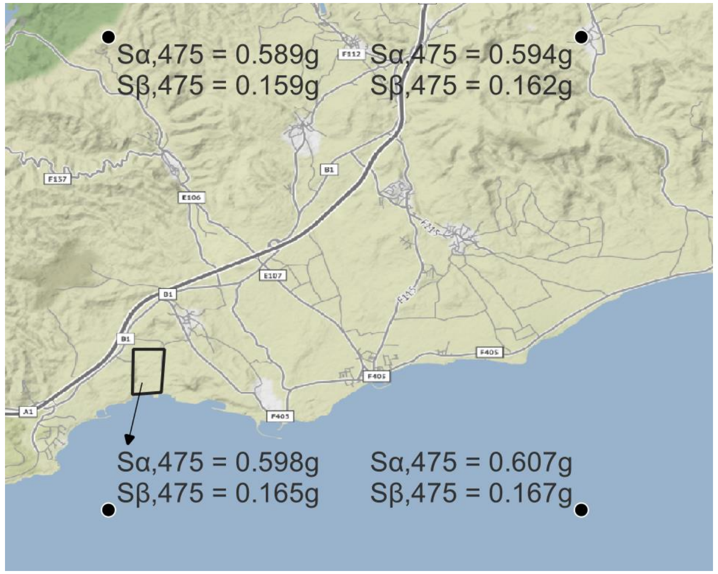
Approach 1 - Current EC8 hazard for 475 years x importance factor **(1.6)**

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

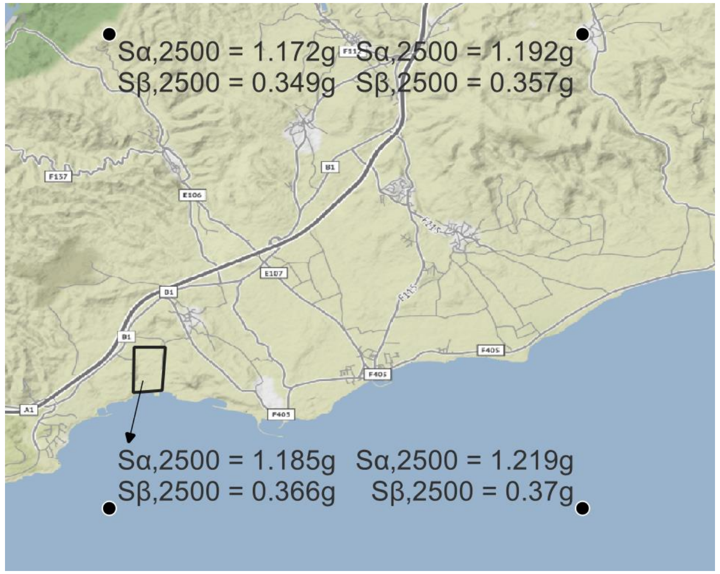
Approach 3 - Revised EC8 with $S_{\alpha,2500}$ and $S_{\beta,2500}$ **from developed hazard maps**



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

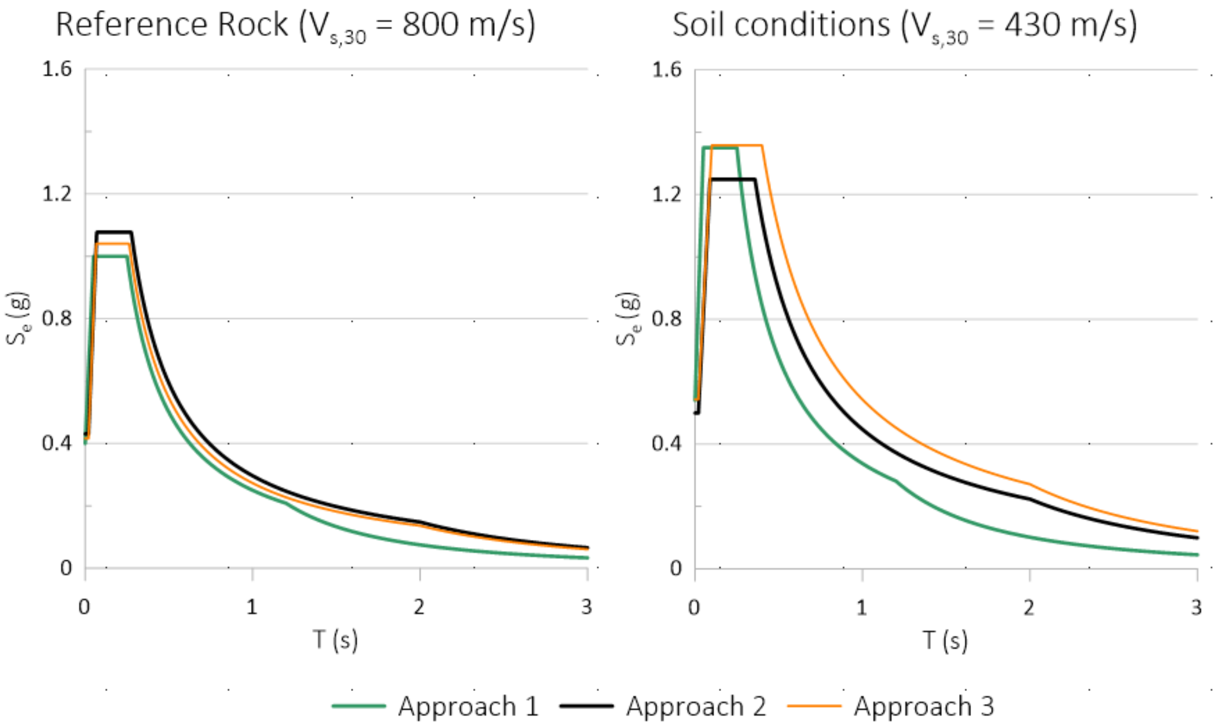
# Application at Vasilikos Power Station in Cyprus

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

Vs,30 ≈ 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)**

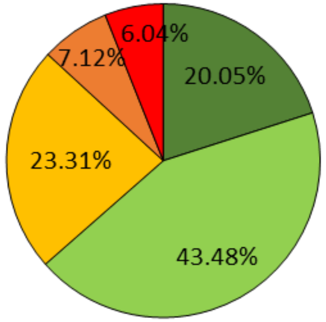
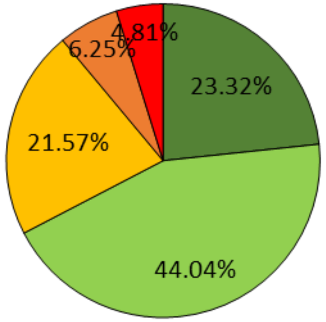
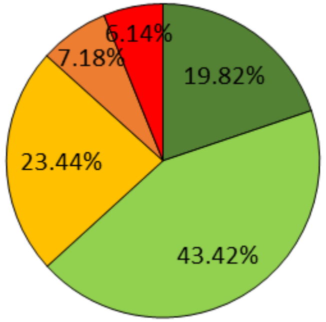
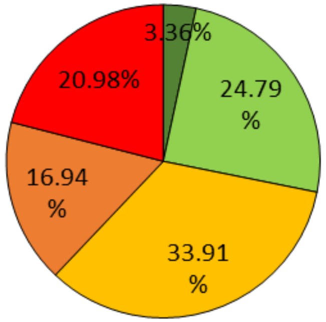
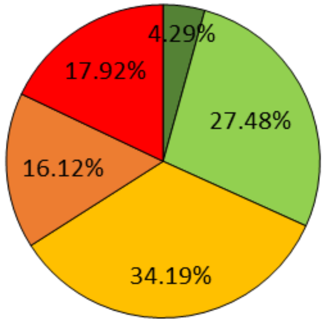
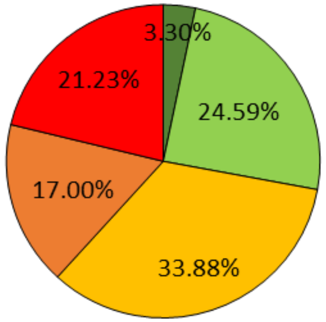


←

**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

| | Approach 1 | Approach 2 | Approach 3 |
|---|---|---|---|
| Anchored |  |  |  |
| Unanchored |  |  |  |

**RP 2500 years**

- 🟩 no damage
- 🟩 slight
- 🟨 moderate
- 🟧 extensive
- 🟥 complete

# 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

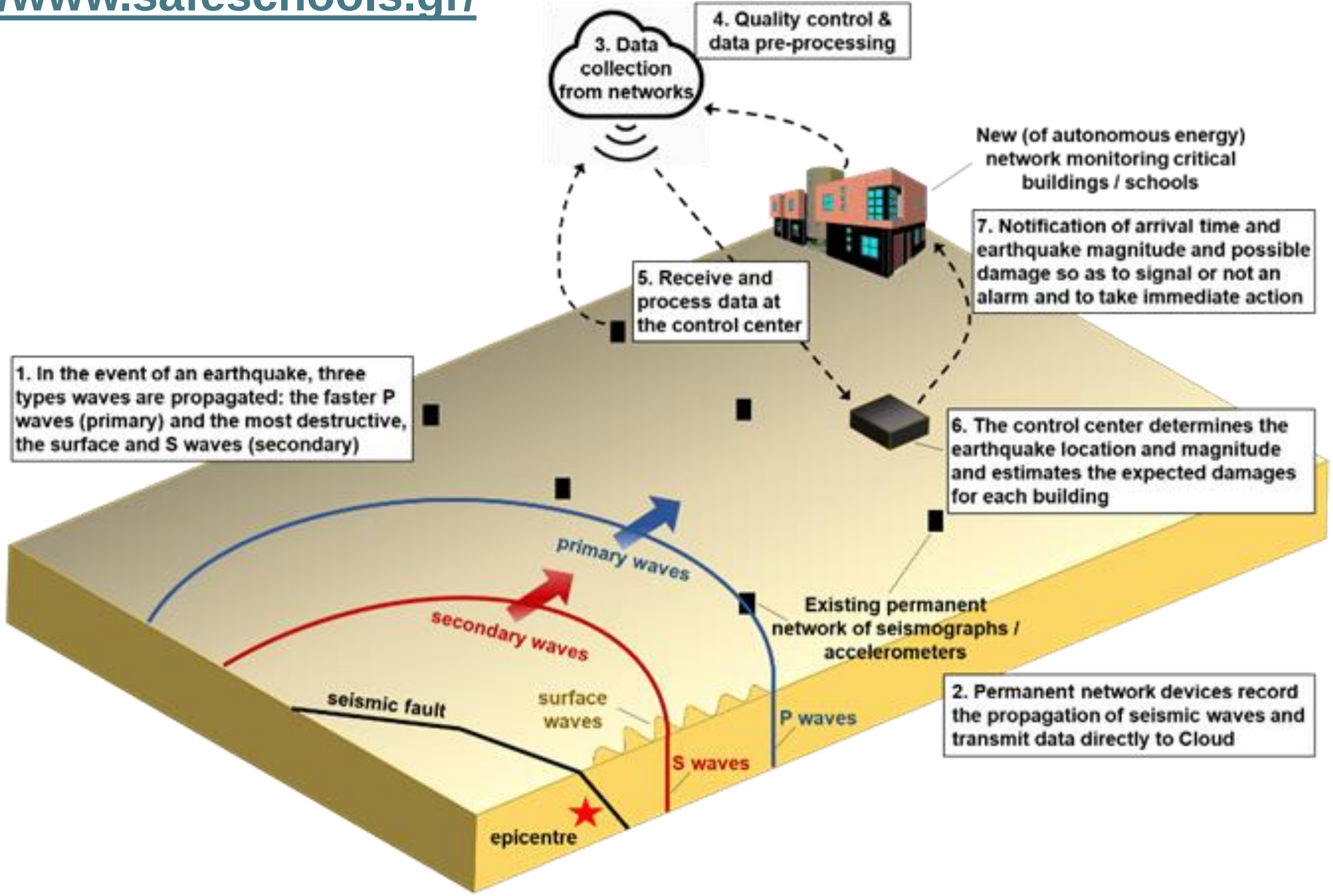
- ❑ Vulnerability and seismic risk assessment of critical infrastructures
  - ❑ Early warning and real time risk assessment (SafeSchools)
  - ❑ Risk assessment of schools  (RiskSchools)
  - ❑ Systemic seismic analysis of critical infrastructures at urban scale

# 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).*

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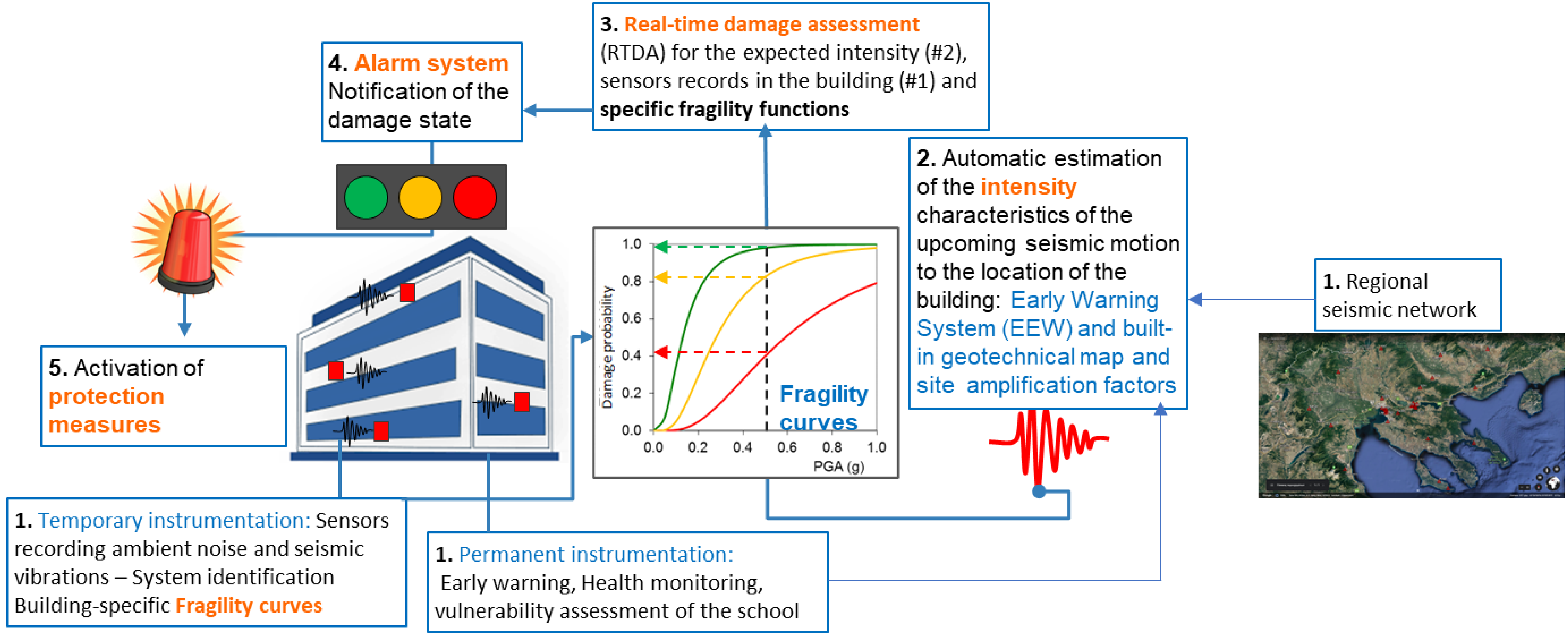
# Concept detailing



**1.** Temporary instrumentation: Sensors recording ambient noise and seismic vibrations – System identification Building-specific **Fragility curves**

**1.** Permanent instrumentation:
Early warning, Health monitoring, vulnerability assessment of the school

**1.** Regional seismic network

**2.** Automatic estimation of the **intensity** characteristics of the upcoming seismic motion to the location of the building: Early Warning System (EEW) and built-in geotechnical map and site amplification factors

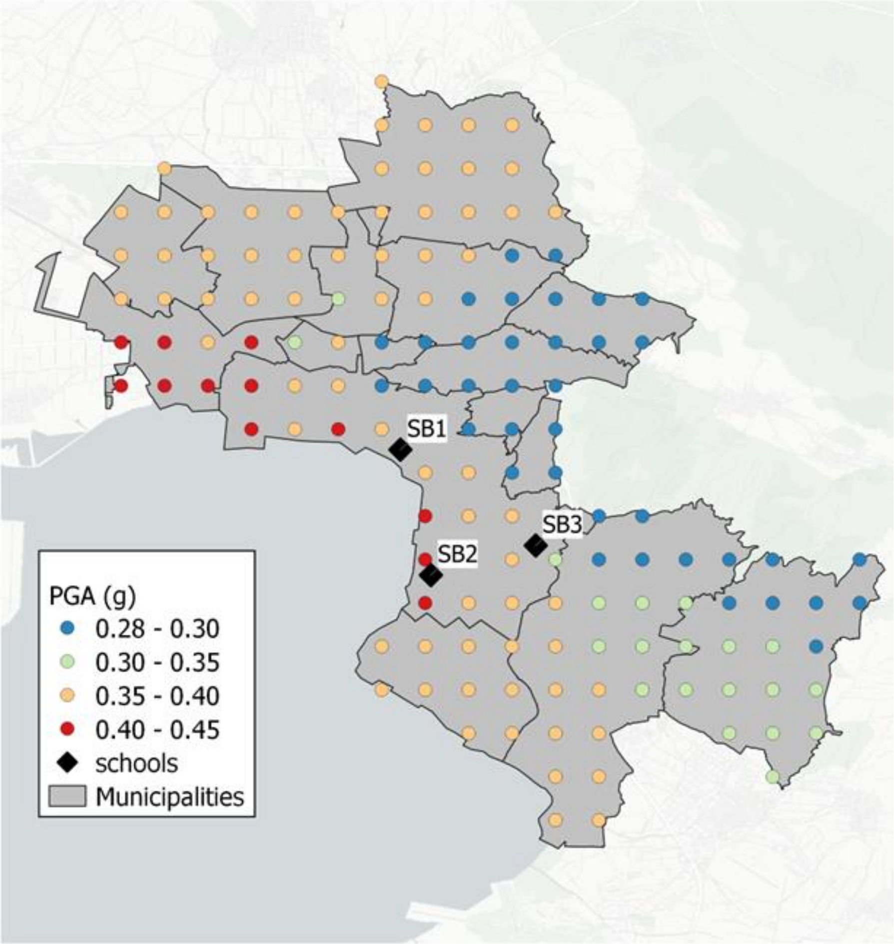
**3.** **Real-time damage assessment** (RTDA) for the expected intensity (#2), sensors records in the building (#1) and **specific fragility functions**

**4.** **Alarm system** Notification of the damage state

**5.** Activation of **protection measures**

https://www.safeschools.gr/

# Application to school buildings



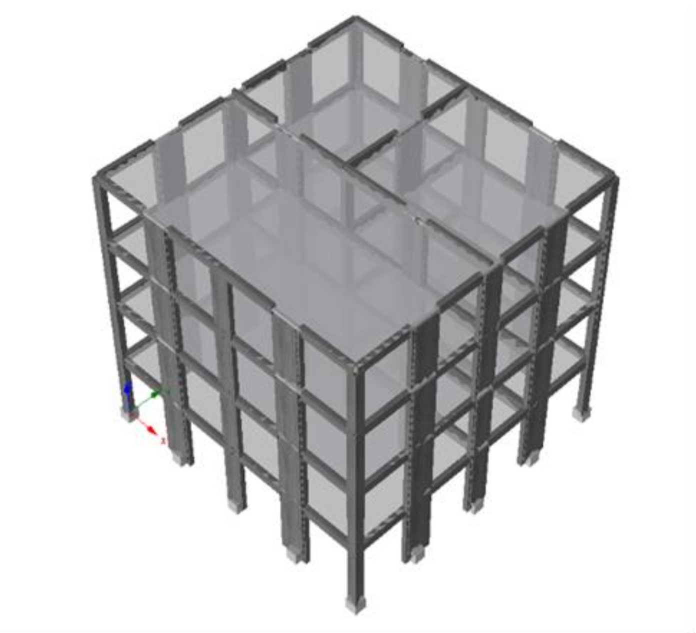
SB1

SB2

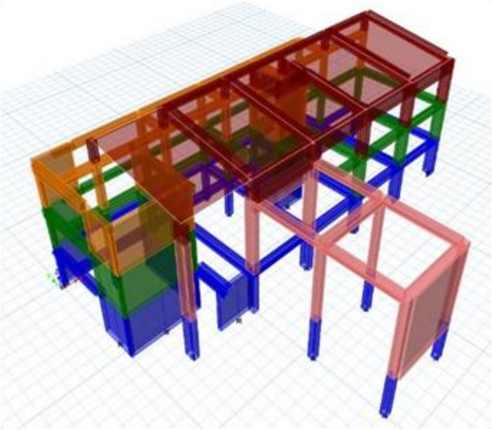
SB3

# Application to school buildings

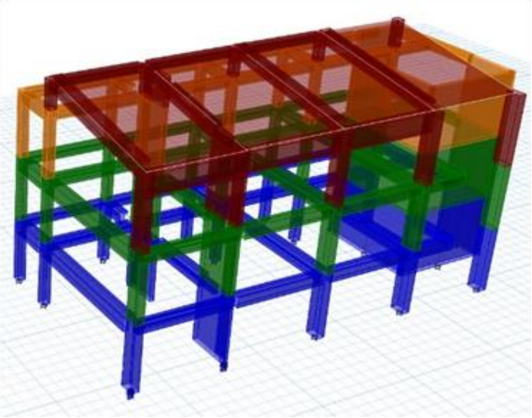
FE model of SB1



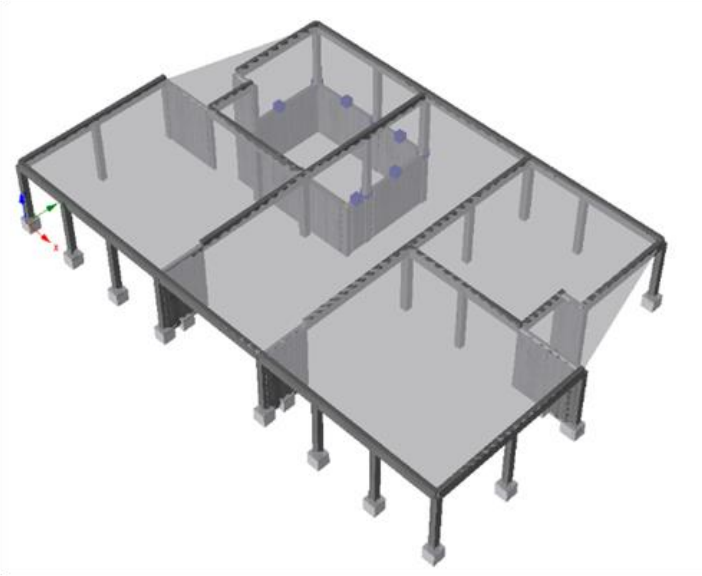
FE model of SB2- part A



FE model of SB2- part B

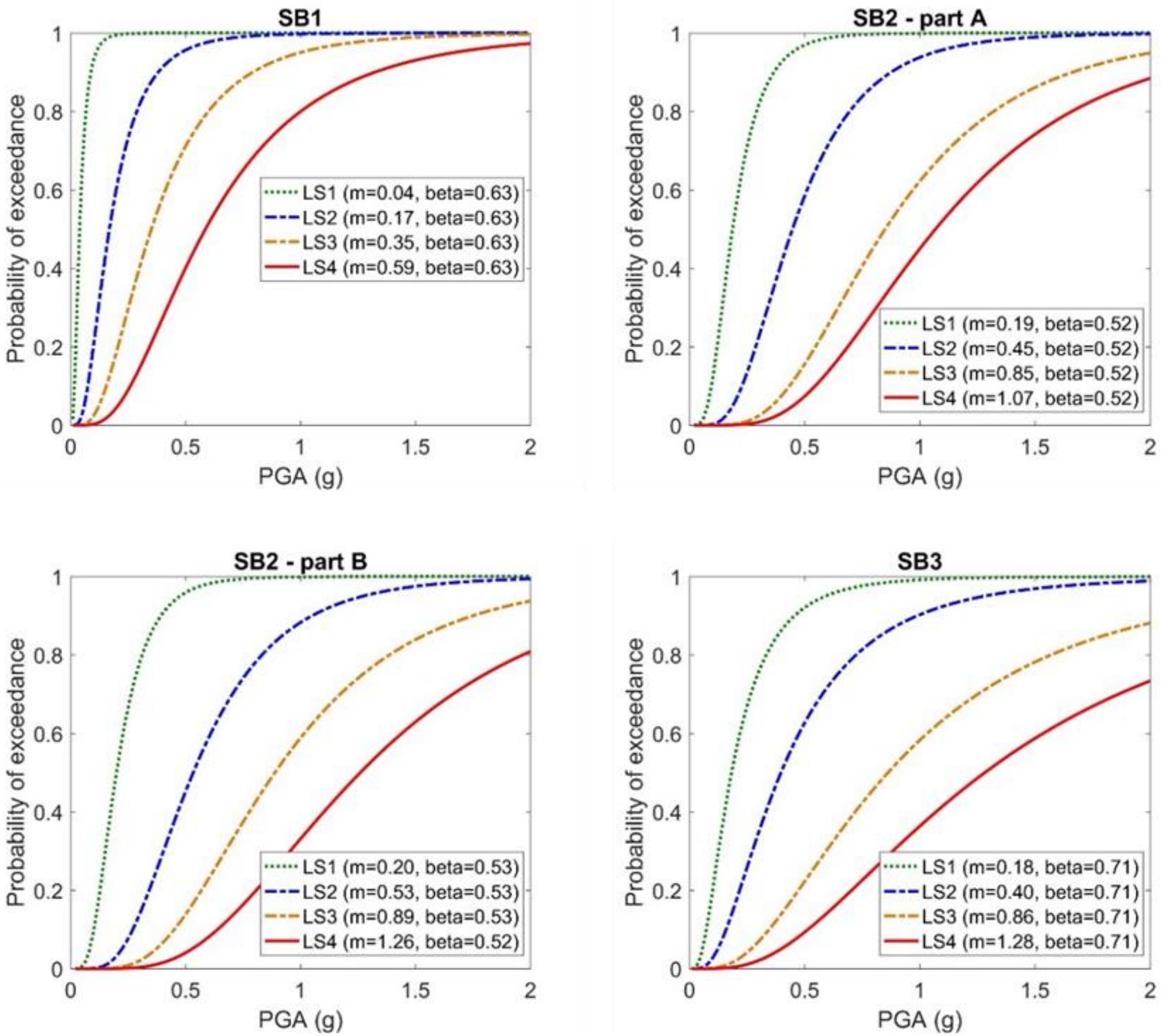


FE model of SB3



# 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.

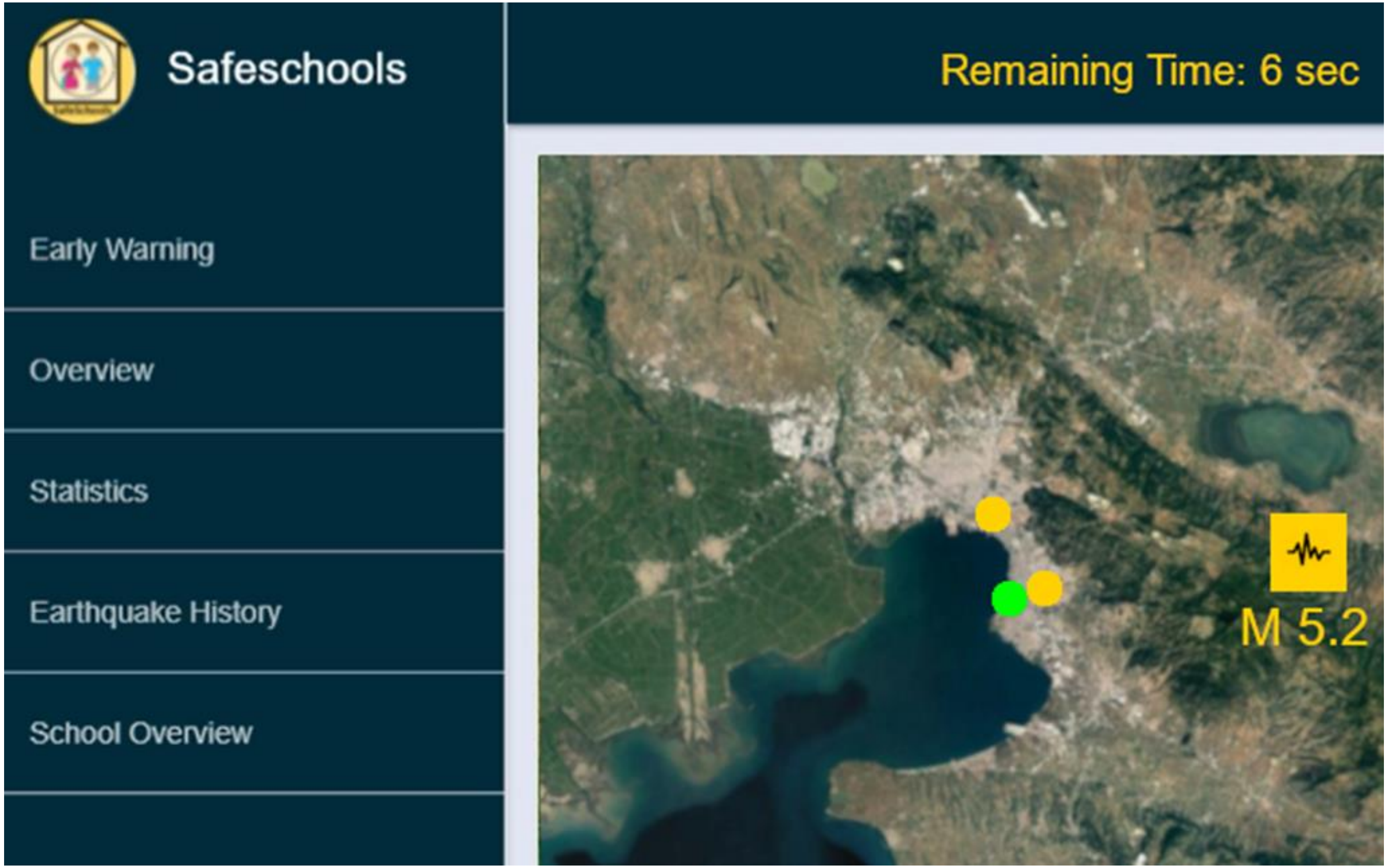
- All information is saved to a central database in a control centre

- 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**

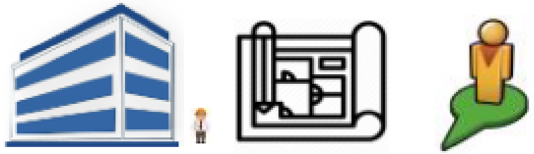
*Karafagka, S., Riga E., Oikonomou G., Karatzetzou A, Fotopoulou, S., Pitilakis D., Pitilakis, K. 2023. RiskSchools: A prioritization-based system for the risk assessment of school buildings combining rapid visual screening smartphone app and detailed vulnerability analysis, Bulletin of Earthquake Engineering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

# Where RiskSchools could be helpful?

- ❑ Evaluate school buildings seismic risk and retrofitting 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

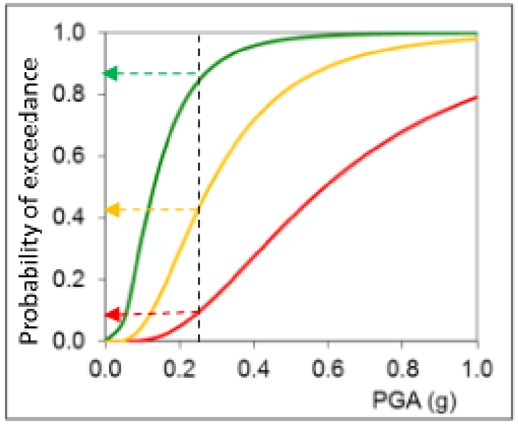
**Building inventory**



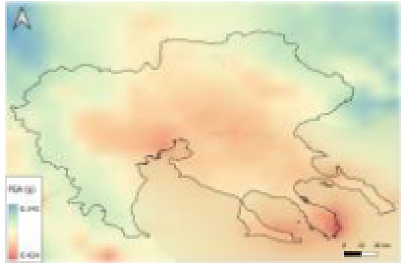
- On-site survey
- Available architectural and structural plans
- Street-view data

**Exposure model**
- Building taxonomy
- Number of buildings/ built area per building class
- Reconstruction cost

**Seismic fragility / vulnerability curves**



**Seismic hazard**



- Local site conditions
- Seismic hazard maps
- Various IMs

**Rapid visual screening (RVS)**
- Technical data
- Seismic hazard zone
- Geotechnical data

**Fragility / Vulnerability analysis**

**Grading of the buildings**
First-order vulnerability assessment

**- Damage assessment**
**- Loss ratio**
Second-order vulnerability assessment

**Expert judgment elicitation**

**Seismic risk classification of buildings**

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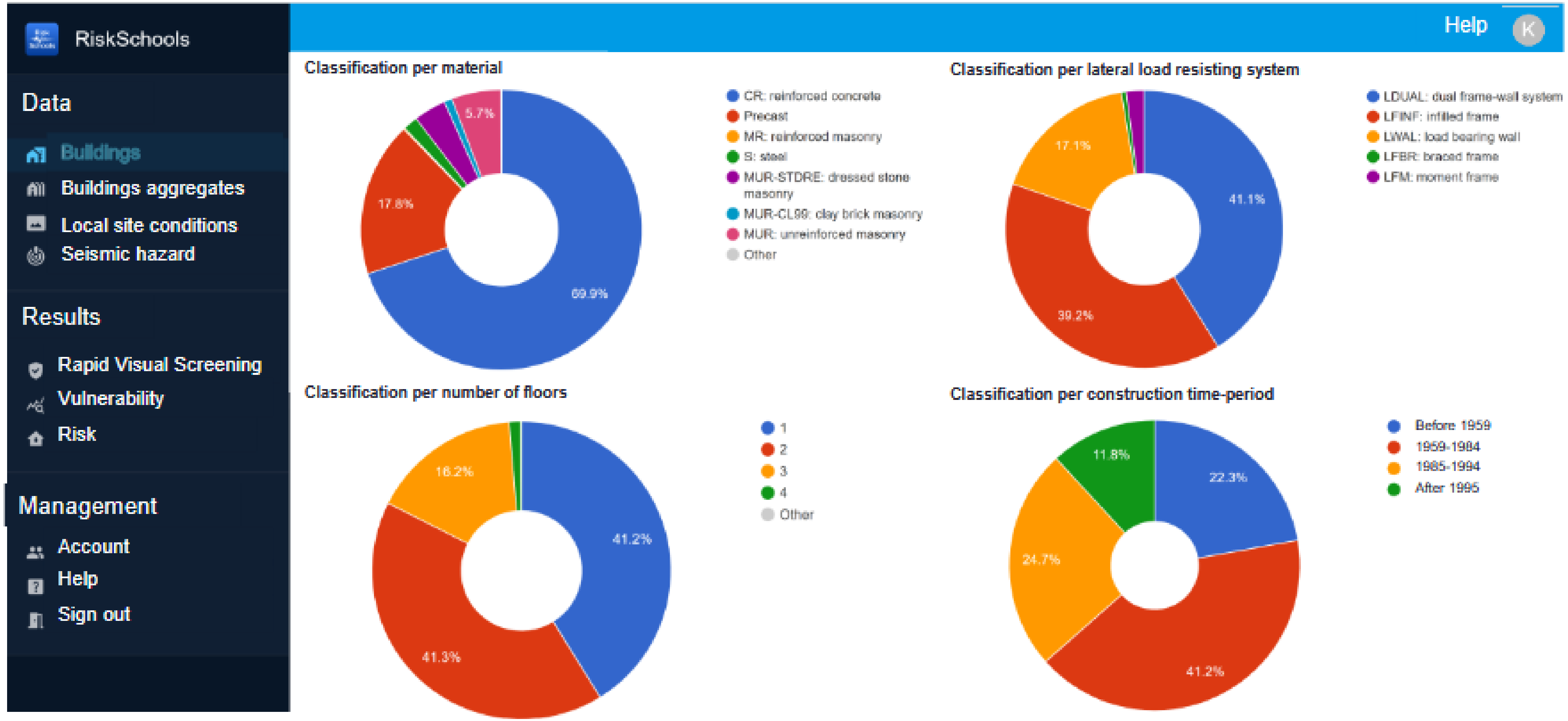
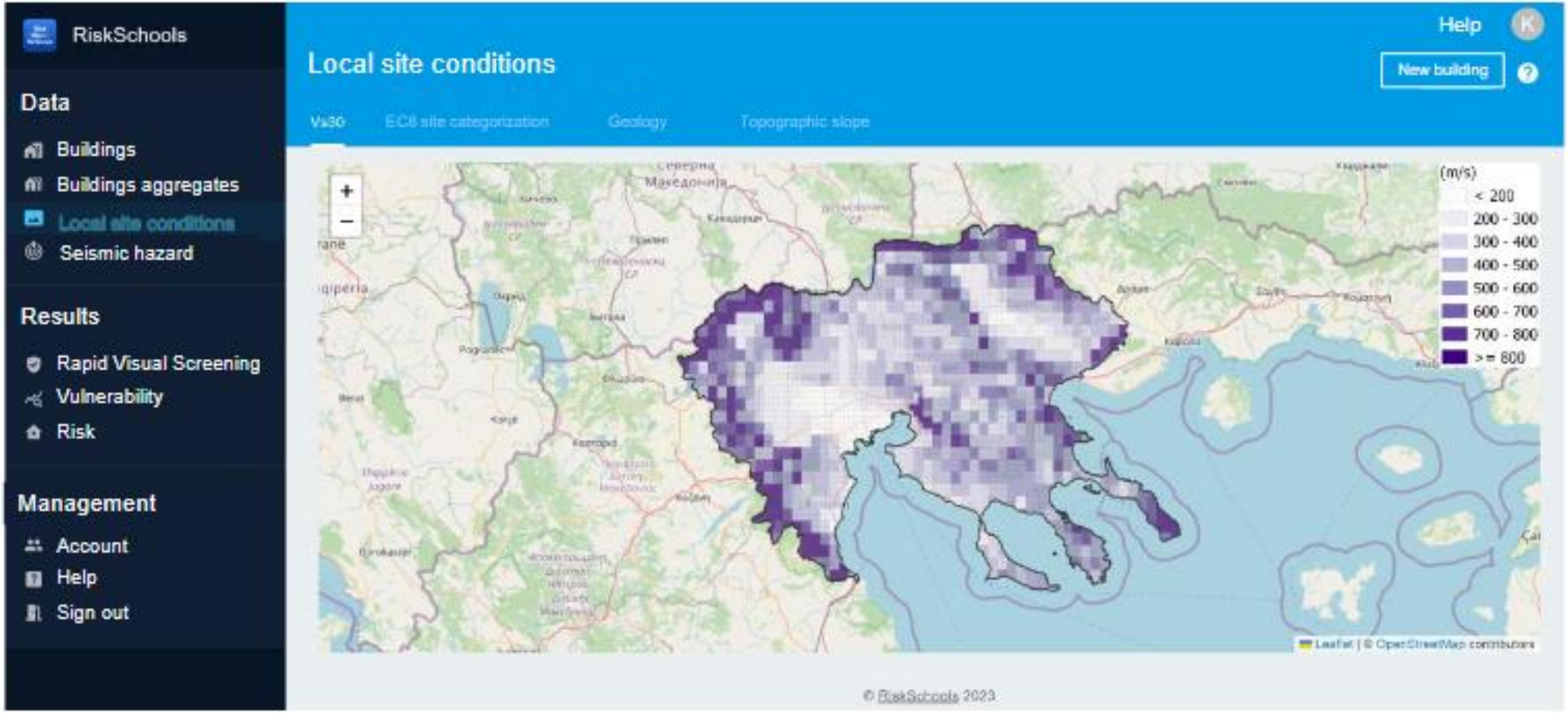
# RiskSchools system – Building statistics



# RiskSchools system – Local site conditions



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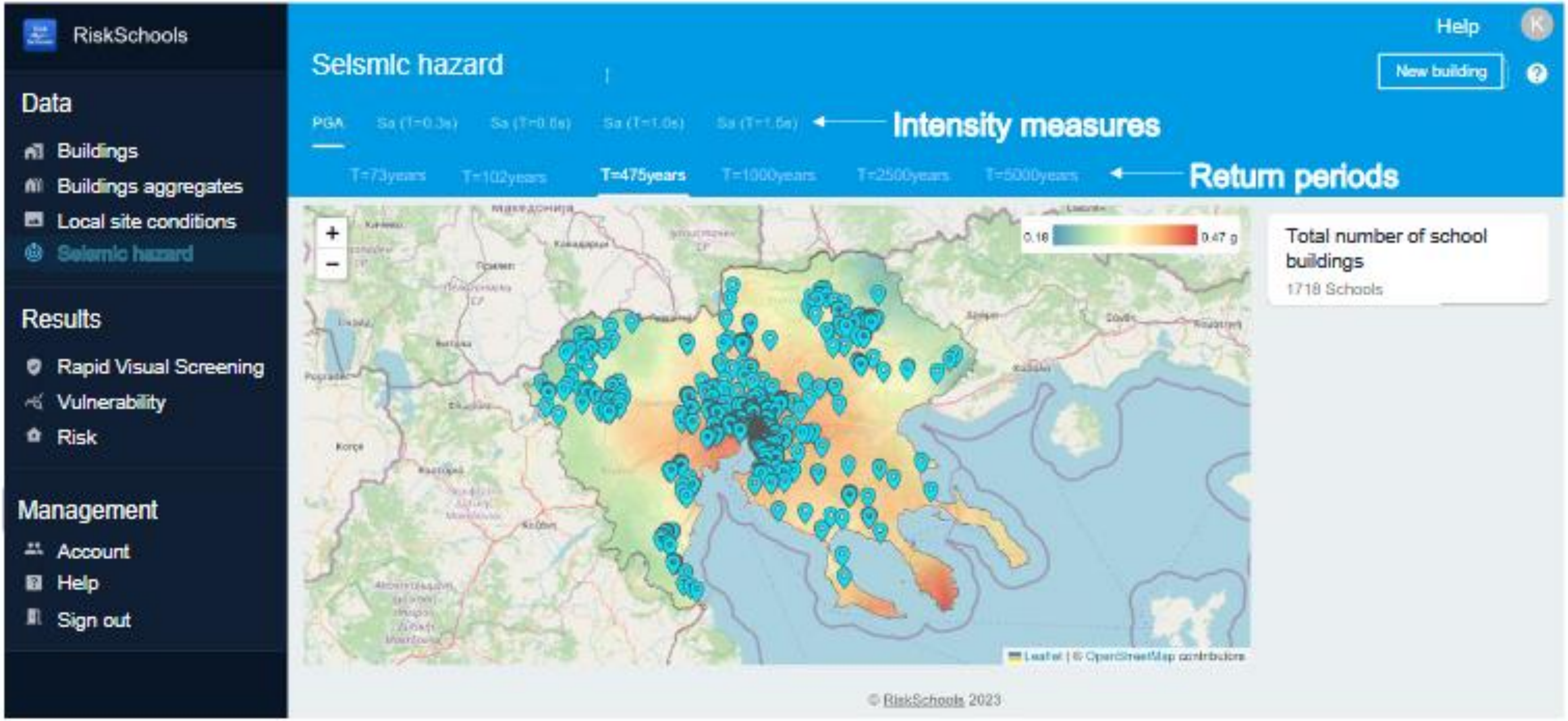
# RiskSchools system – Seismic hazard



Intensity measures

Return periods

Total number of school buildings
1718 Schools

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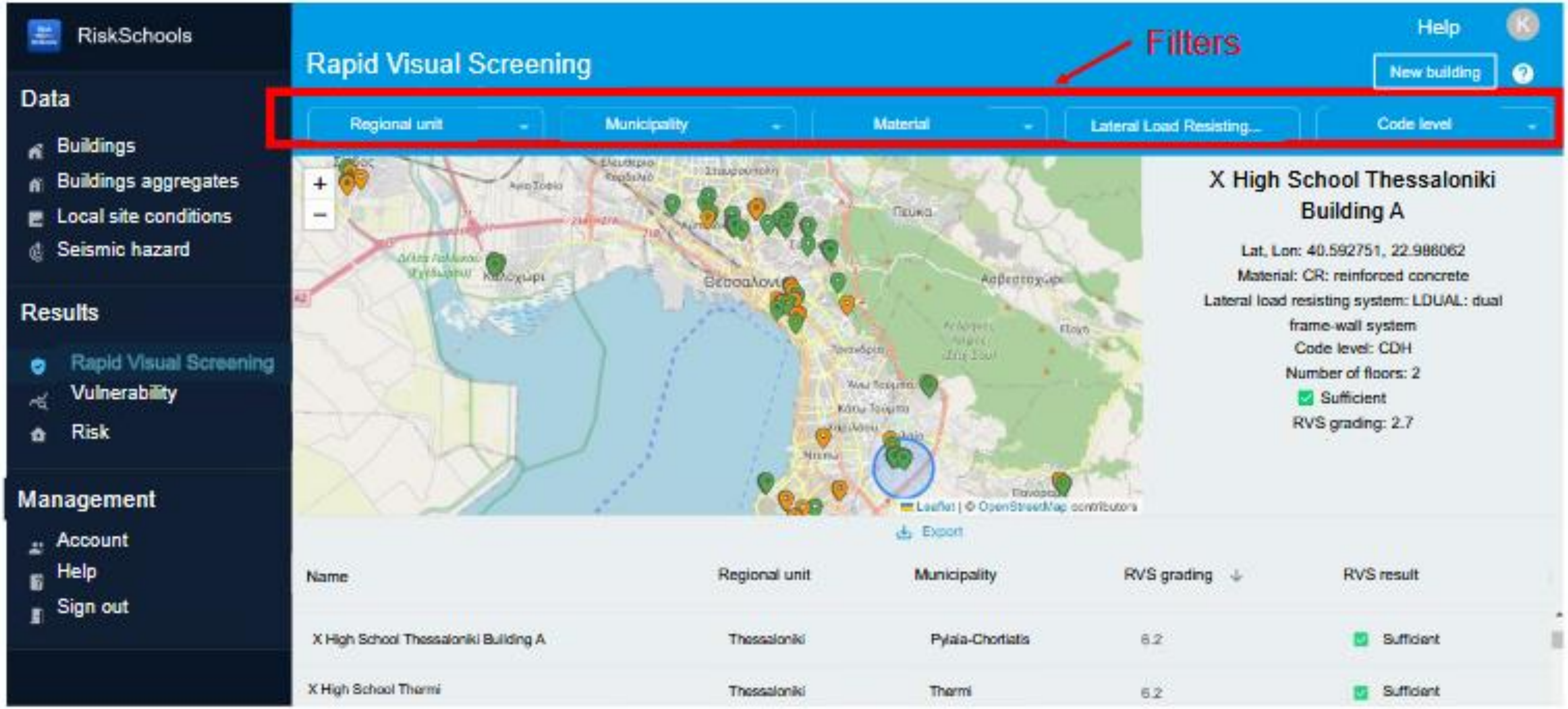
# RiskSchools system – Rapid Visual Screening



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 | ✓ Sufficient |
| X High School Thermi | Thessaloniki | Thermi | 6.2 | ✓ Sufficient |

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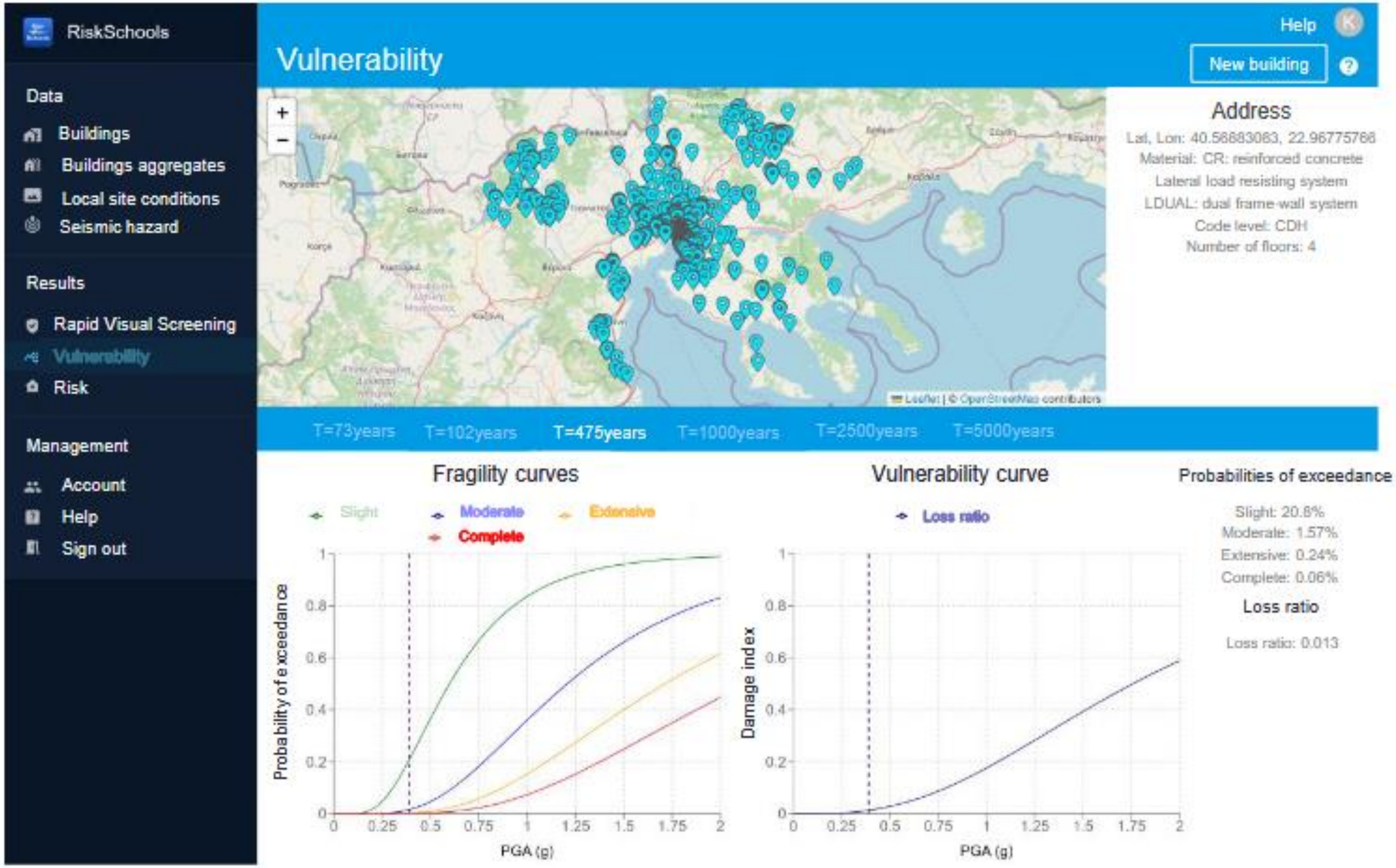
# RiskSchools system - Vulnerability



Address

Lat, Lon: 40.58883083, 22.96775788
Material: CR: reinforced concrete
Lateral load resisting system
LDUAL: dual frame-wall system
Code level: CDH
Number of floors: 4

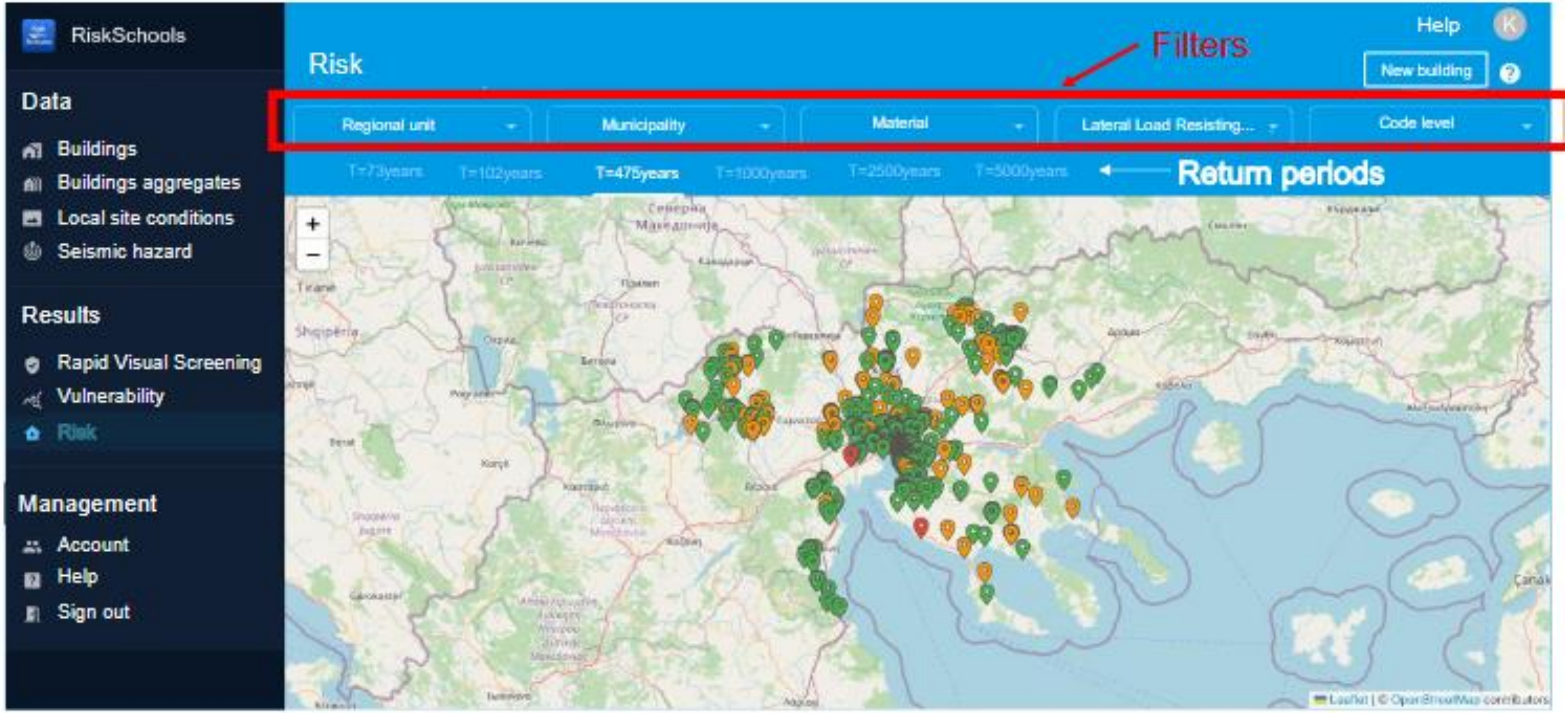
Probabilities of exceedance

Slight: 20.8%
Moderate: 1.57%
Extensive: 0.24%
Complete: 0.06%

Loss ratio

Loss ratio: 0.013

# RiskSchools system - Risk



Filters

Return periods

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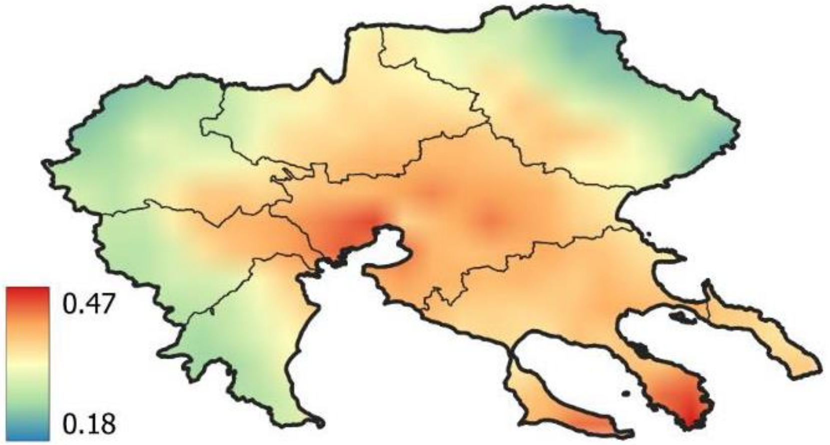
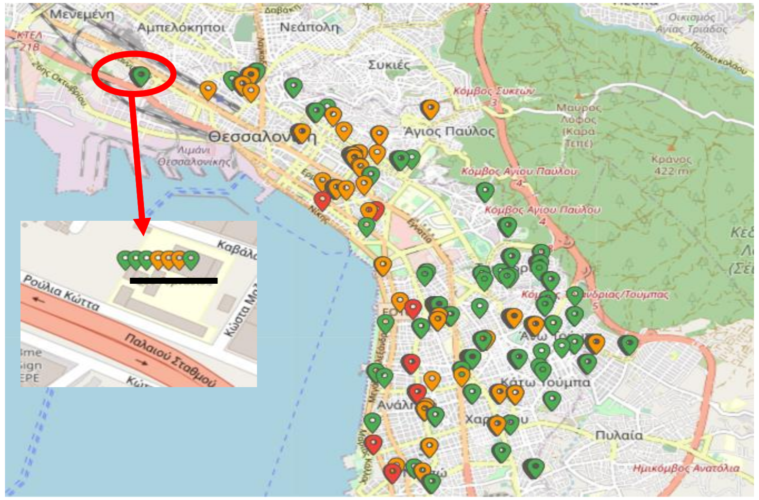
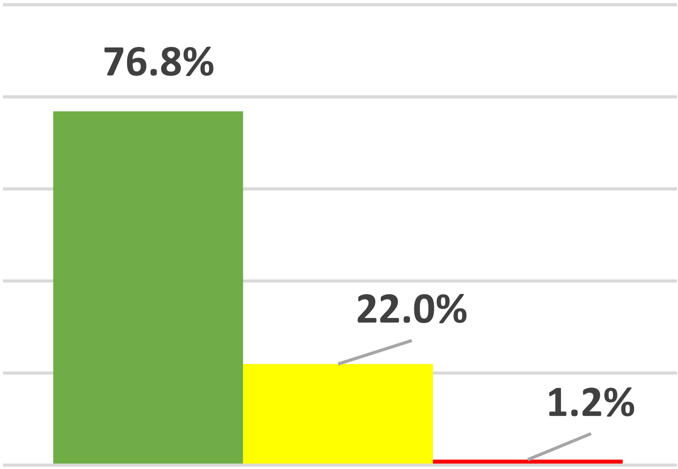
# Application to the school buildings of Central Macedonia

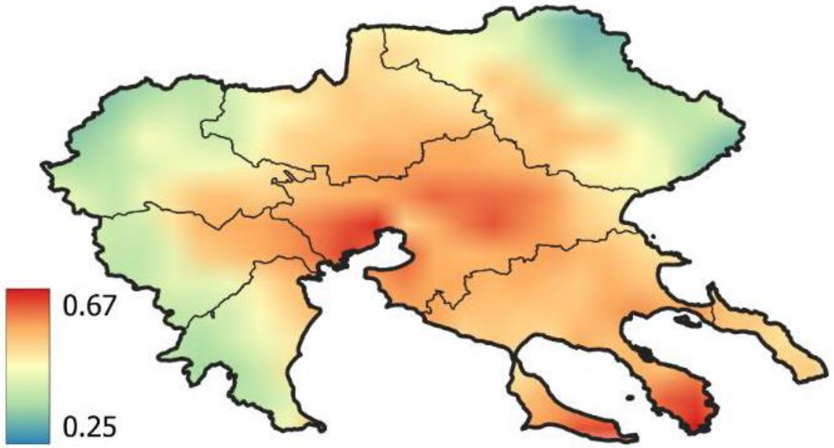
## T = 475 years

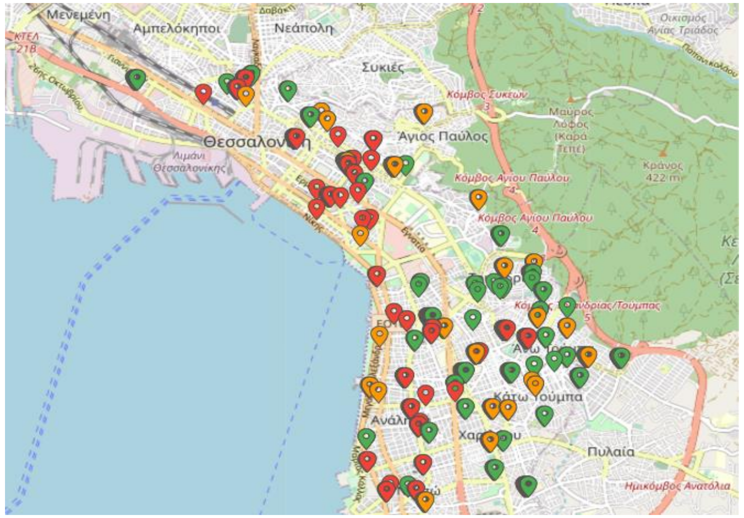


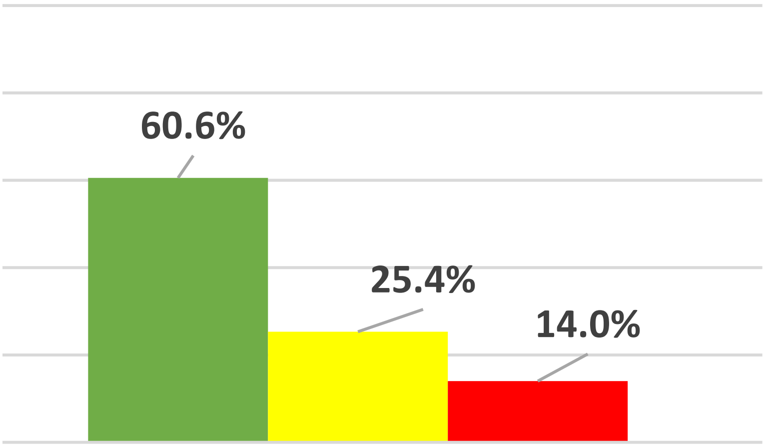




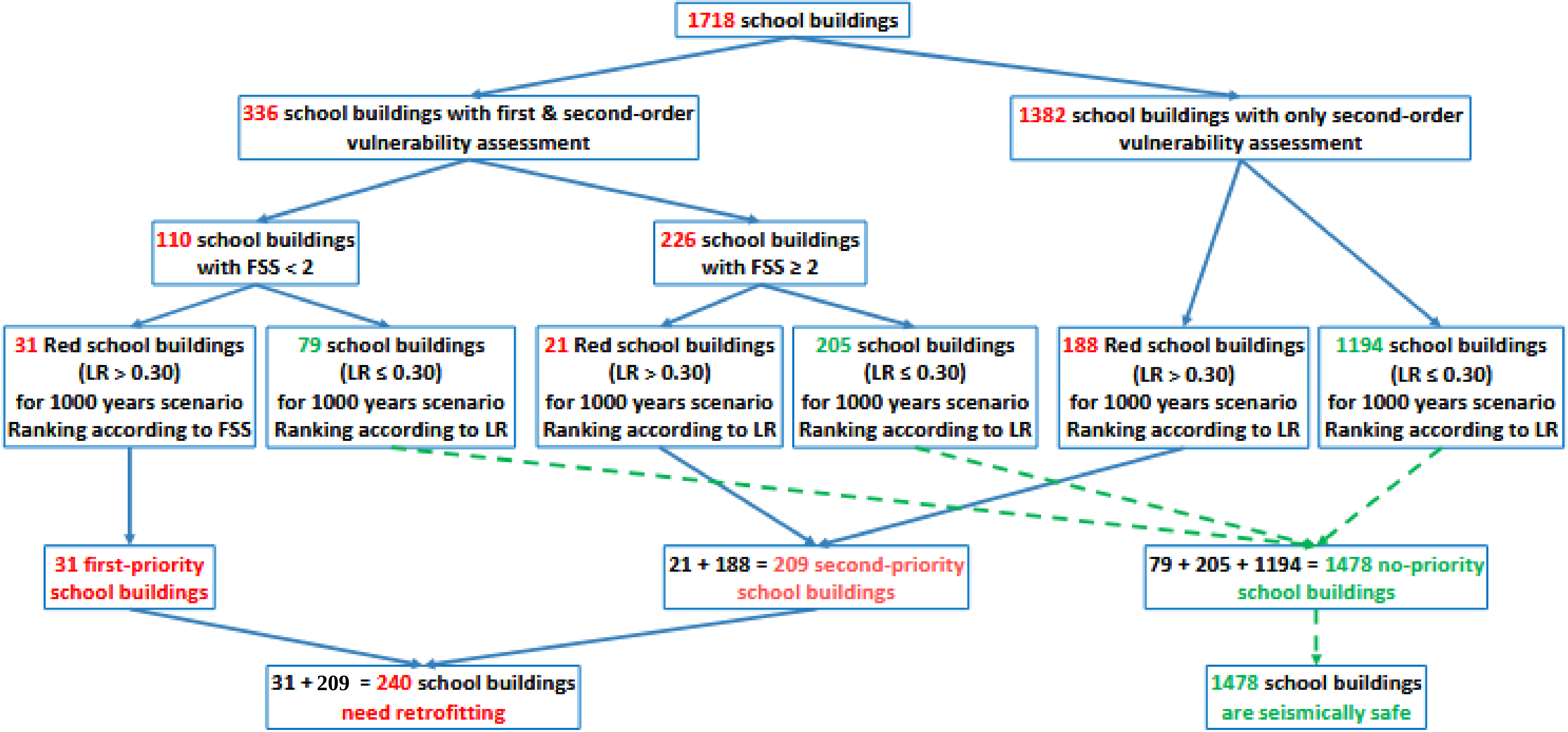
## T = 1000 years







# Application to the school buildings of Central Macedonia



1718 school buildings

336 school buildings with first & second-order vulnerability assessment

1382 school buildings with only second-order vulnerability assessment

110 school buildings with FSS < 2

226 school buildings with FSS ≥ 2

31 Red school buildings (LR > 0.30) for 1000 years scenario Ranking according to FSS

79 school buildings (LR ≤ 0.30) for 1000 years scenario Ranking according to LR

21 Red school buildings (LR > 0.30) for 1000 years scenario Ranking according to LR

205 school buildings (LR ≤ 0.30) for 1000 years scenario Ranking according to LR

188 Red school buildings (LR > 0.30) for 1000 years scenario Ranking according to LR

1194 school buildings (LR ≤ 0.30) for 1000 years scenario Ranking according to LR

31 first-priority school buildings

21 + 188 = 209 second-priority school buildings

79 + 205 + 1194 = 1478 no-priority school buildings

31 + 209 = 240 school buildings need retrofitting

1478 school buildings are seismically safe

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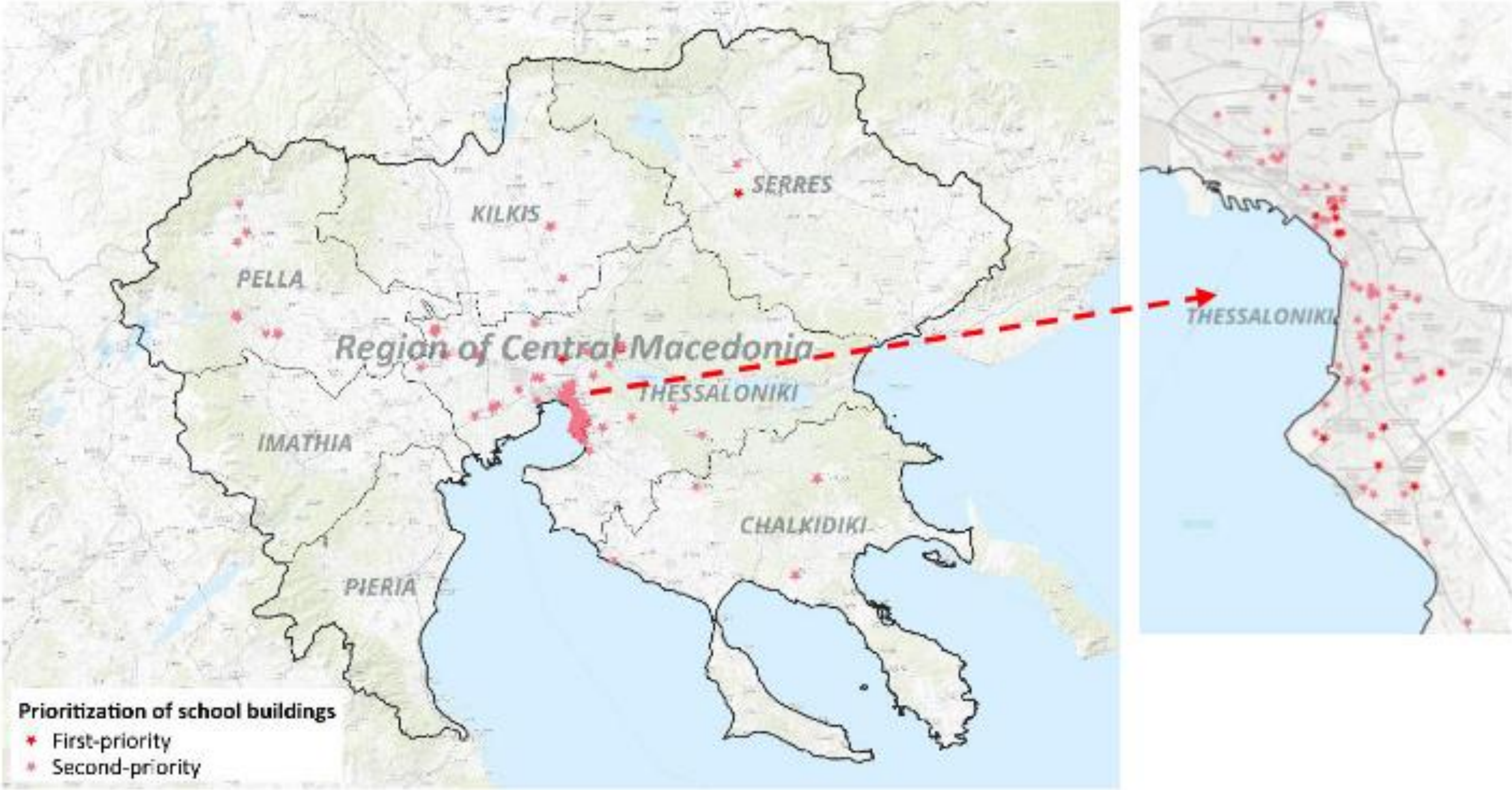
# Application to the school buildings of Central Macedonia



# Systemic seismic risk analysis

SYNER-G

*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

SYNER-G

GEM
GLOBAL EARTHQUAKE MODEL
working together to assess risk

OQ
OPENQUAKE
calculate share explore

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

Poudel A, Pitilakis K, Silva V, Rao A (2023) Infrastructure Seismic Risk Assessment: An Overview and Integration to Contemporary Open Tool Towards Global Usage, Bulletin of Earthquake Engineering, doi.org/10.1007/s10518-023-01693-z

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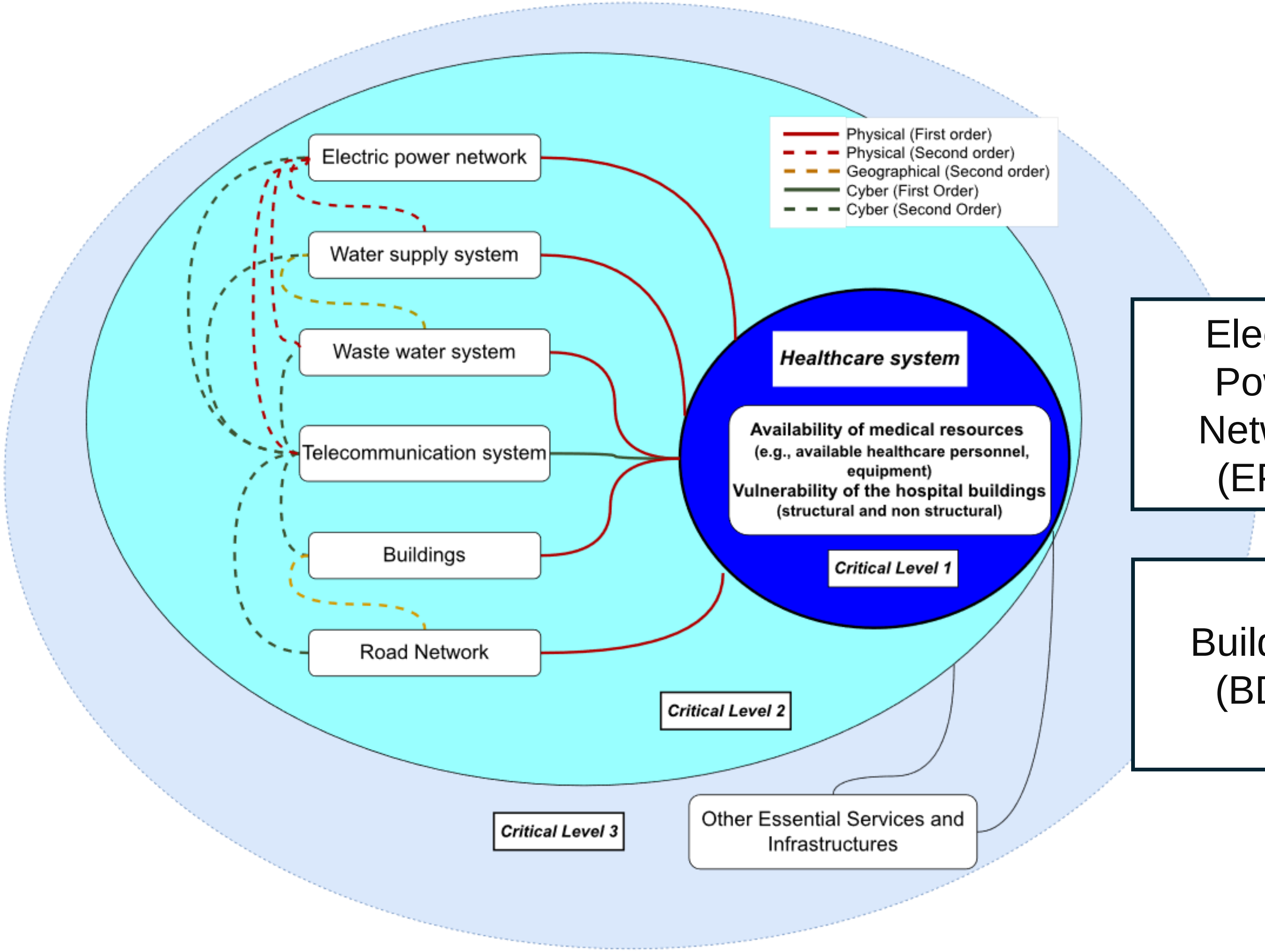
# Systemic Seismic Risk of Critical Infrastructures at Urban Scale

## Interdependencies with respect to the **healthcare system**

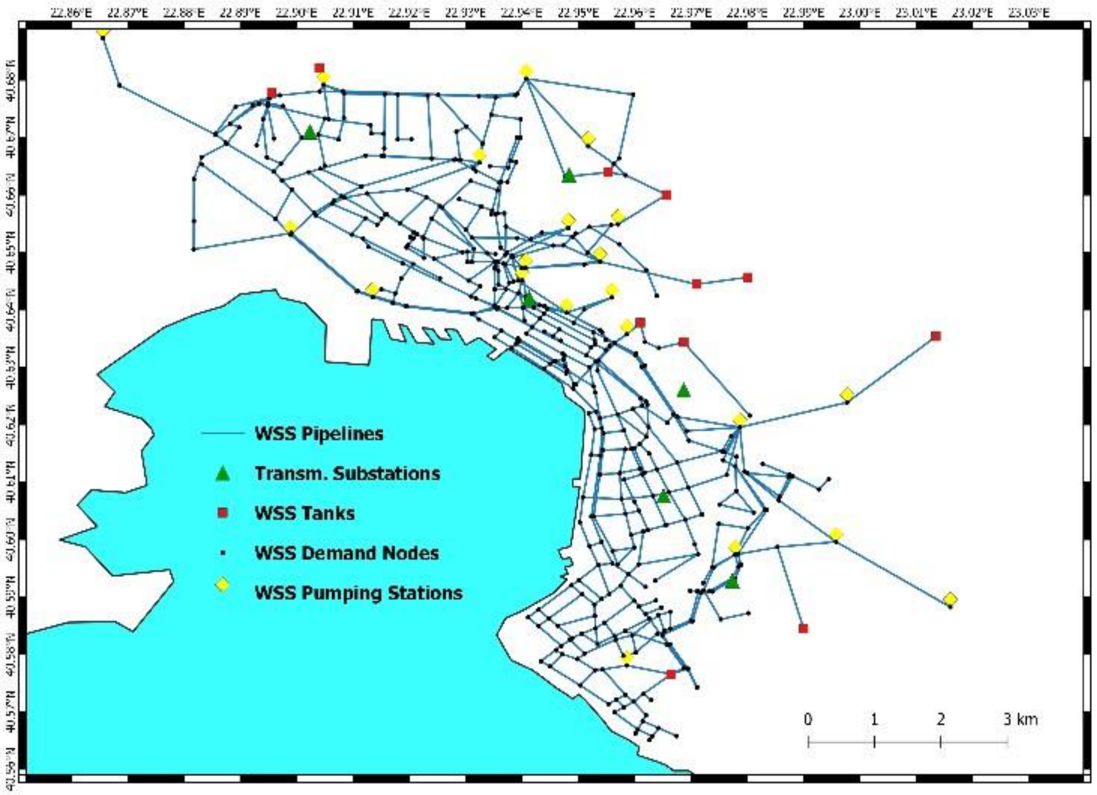


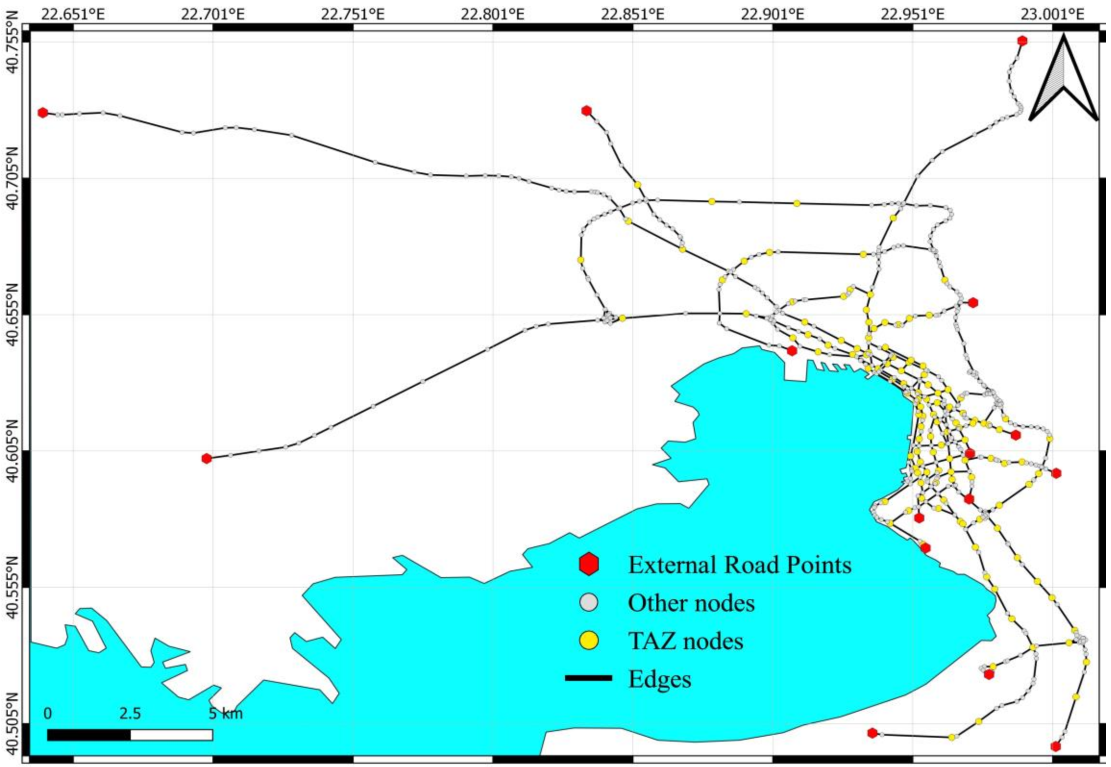
Electric Power Network (EPN) → First Order, Physical Interdependencies → Healthcare System (HCS)

Electric Power Network (EPN) → Second Order, Physical Interdependencies → Water Supply System (WSS) → First Order, Physical Interdependencies → Healthcare System (HCS)

Buildings (BDG) → Second Order, Geographical Interdependencies → Road Network (RDN) → First Order, Physical Interdependencies → Healthcare System (HCS)

# Water, electrical power and road systems in Thessaloniki





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# 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)

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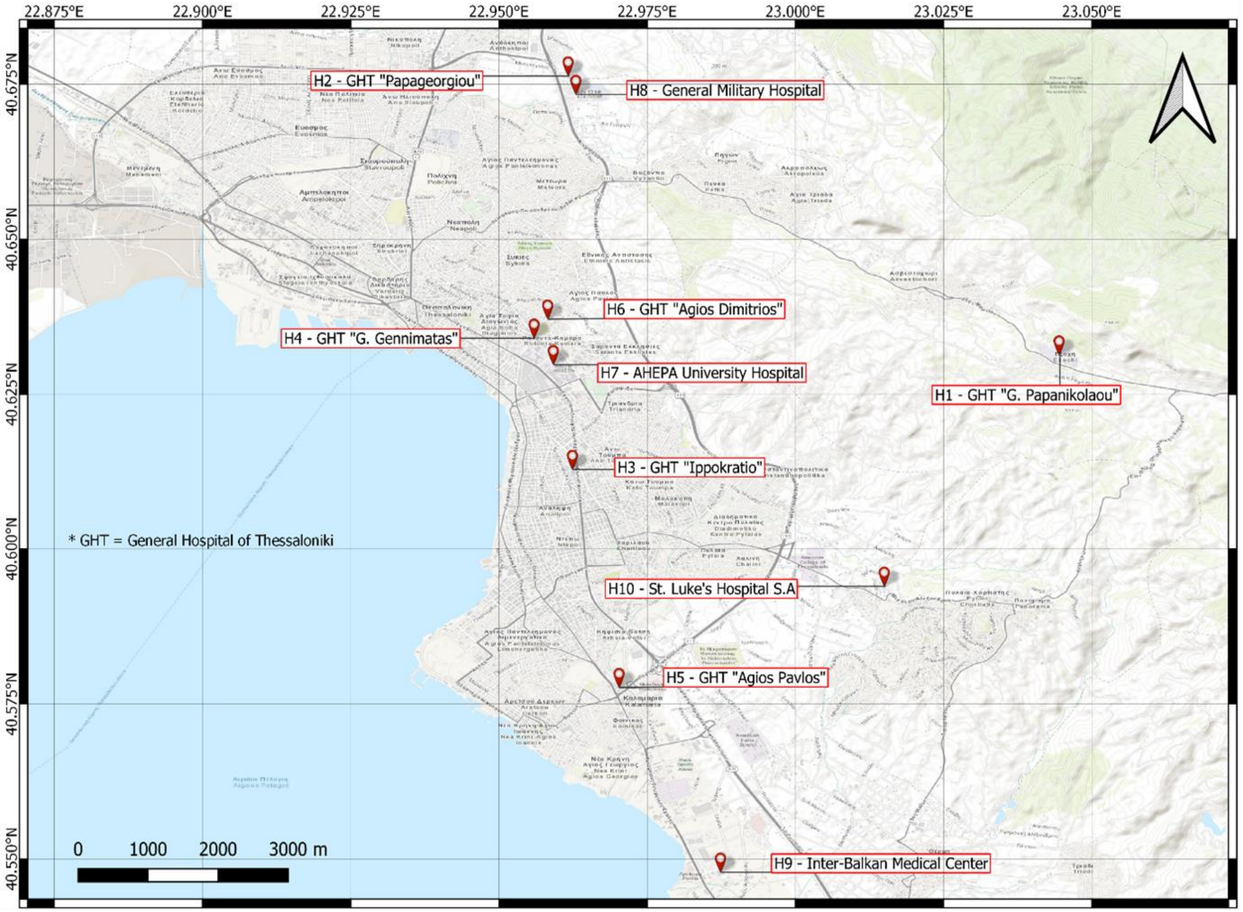
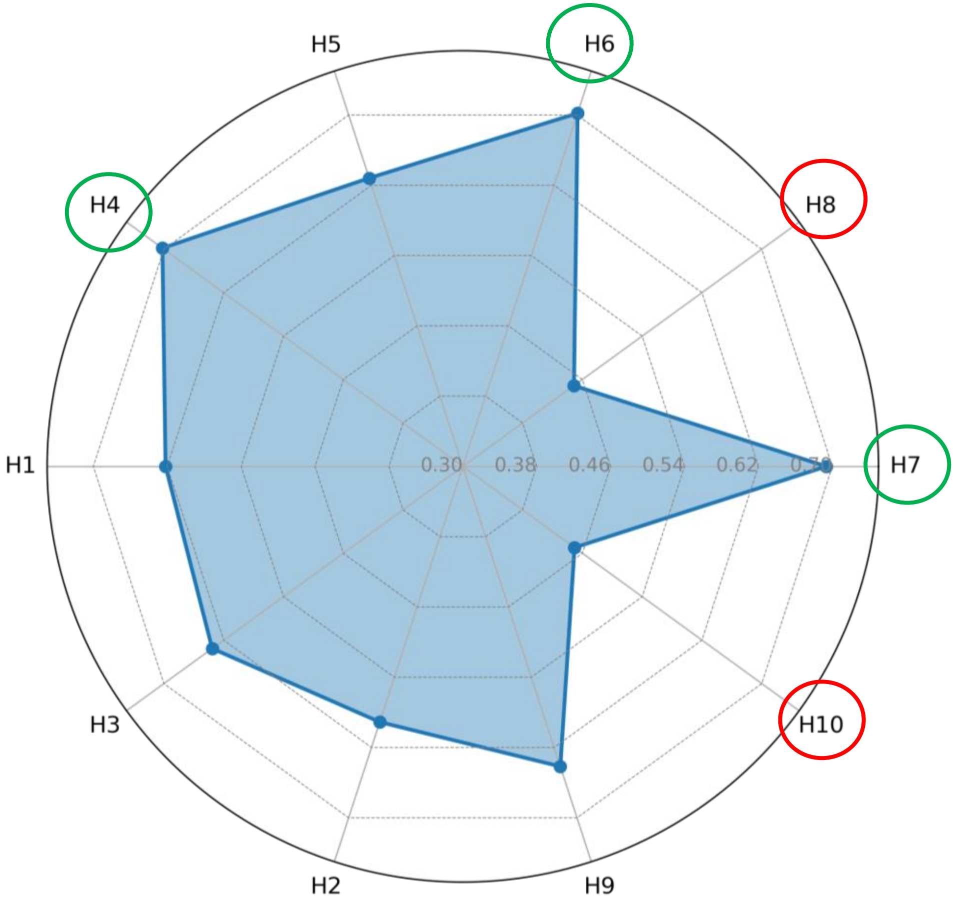
# Performance of the Hospitals



| | |
|---|---|
| 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



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

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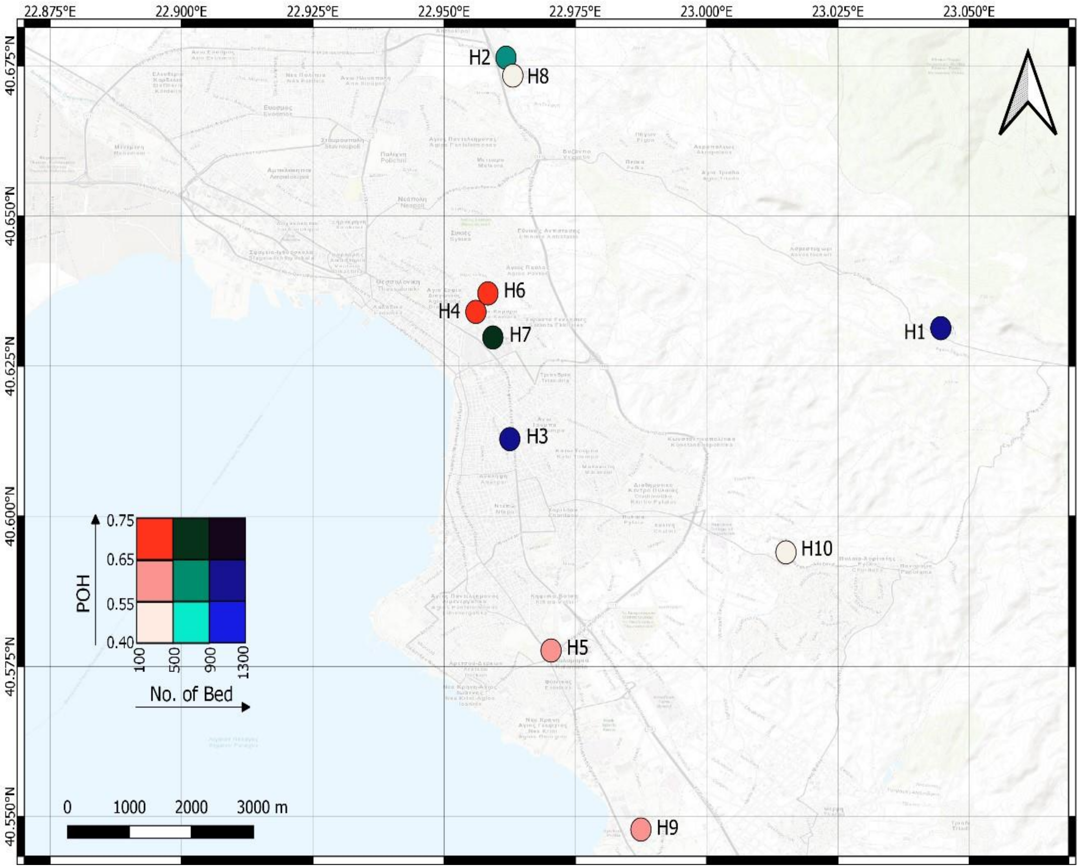
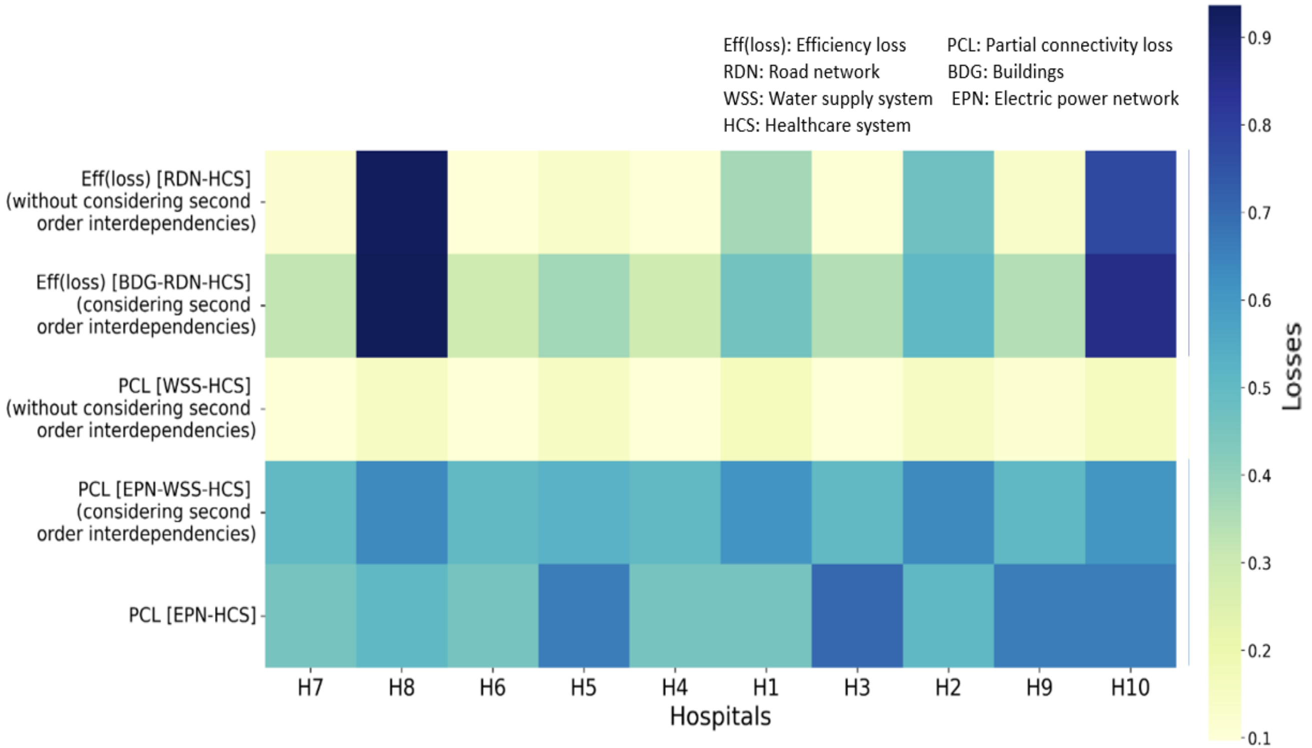
# Systemic Seismic Risk of Critical Infrastructures at Urban Scale

## 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