



Anastasios Sextos

Associate Professor



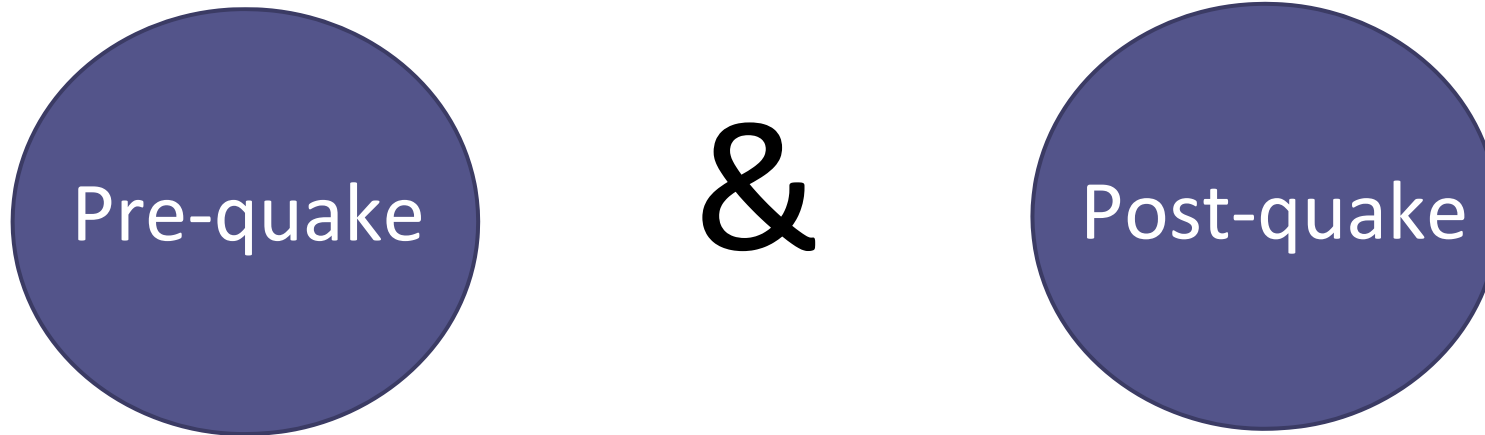
University of
Bristol



Aristotle University
Thessaloniki

Resilience-based Seismic Design

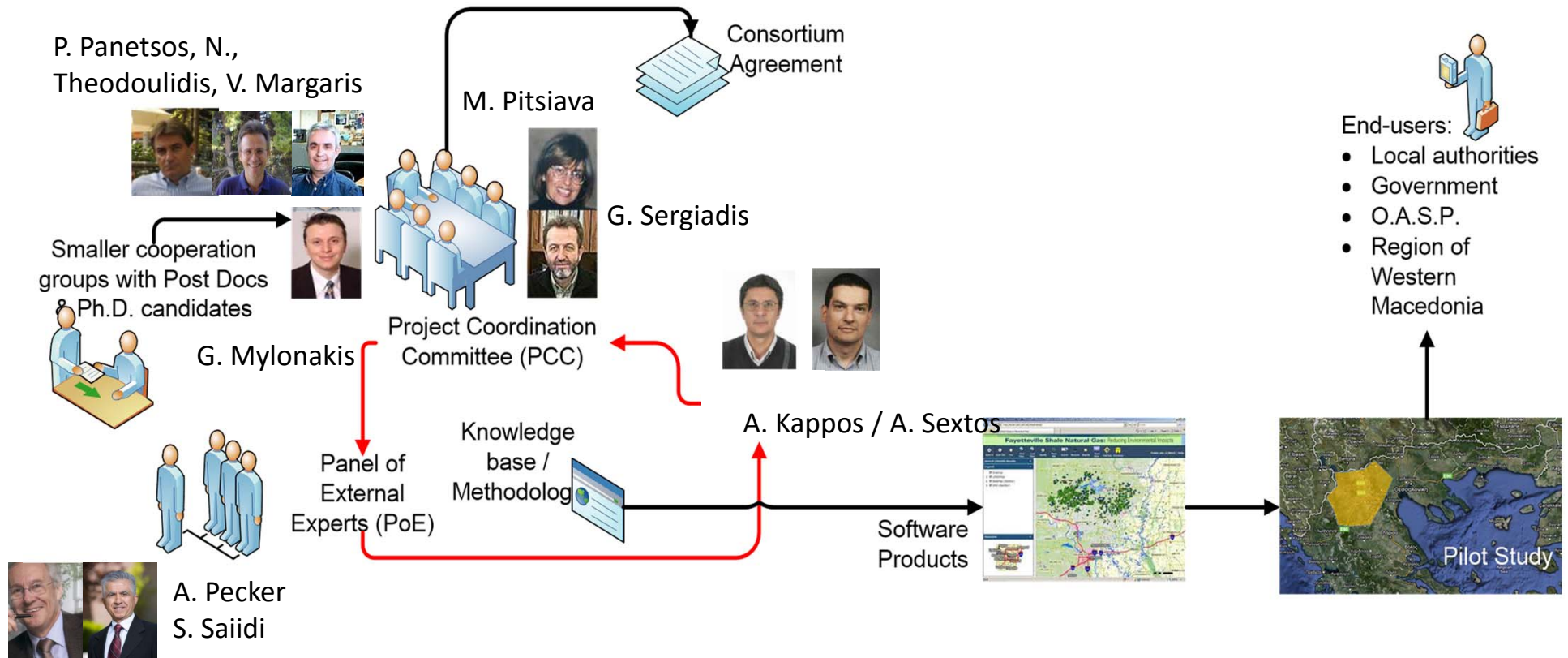
Wider Performance Criteria



Mitigate Seismic Risk (in terms of direct damage and loss)

Minimize implications on disaster response (immediate after) and recovery (in the long term)

Real-Time Seismic Risk of Intercity Highway Networks



Concept

Objectives

Methodology

Pilot Study

Conclusions

Objective

Risk-informed Decision Making of Highway Networks

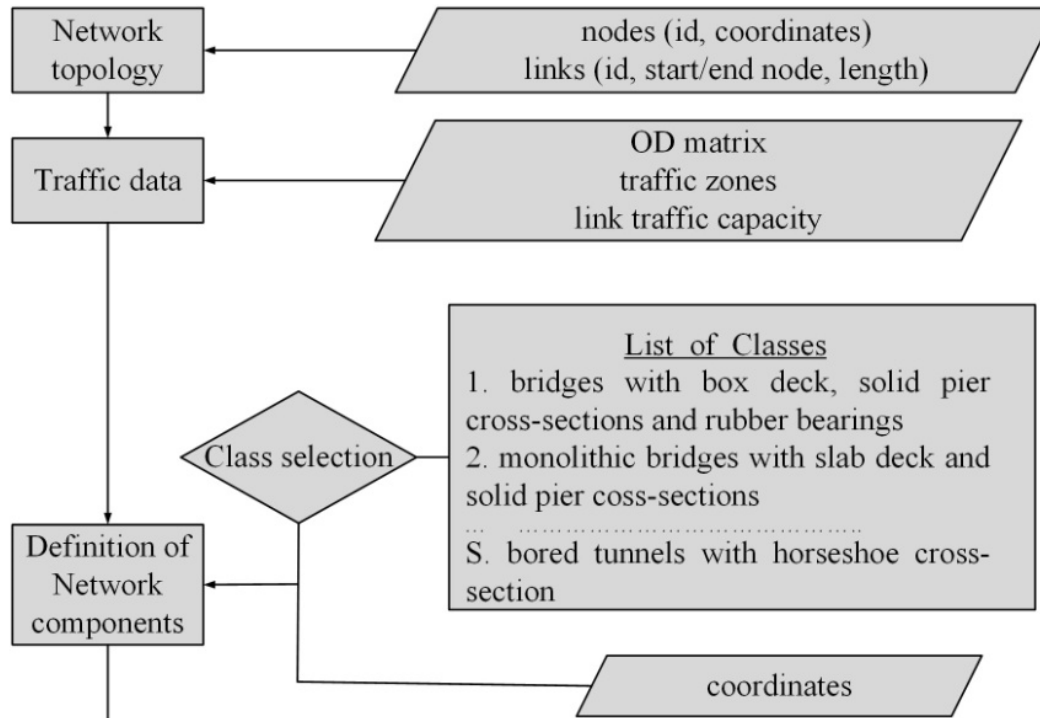
for

State & Stakeholders

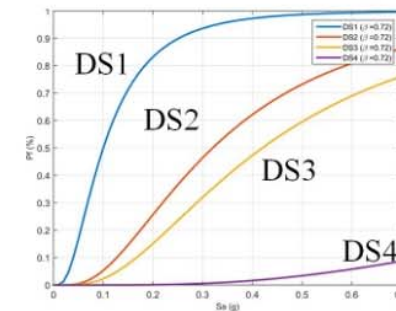
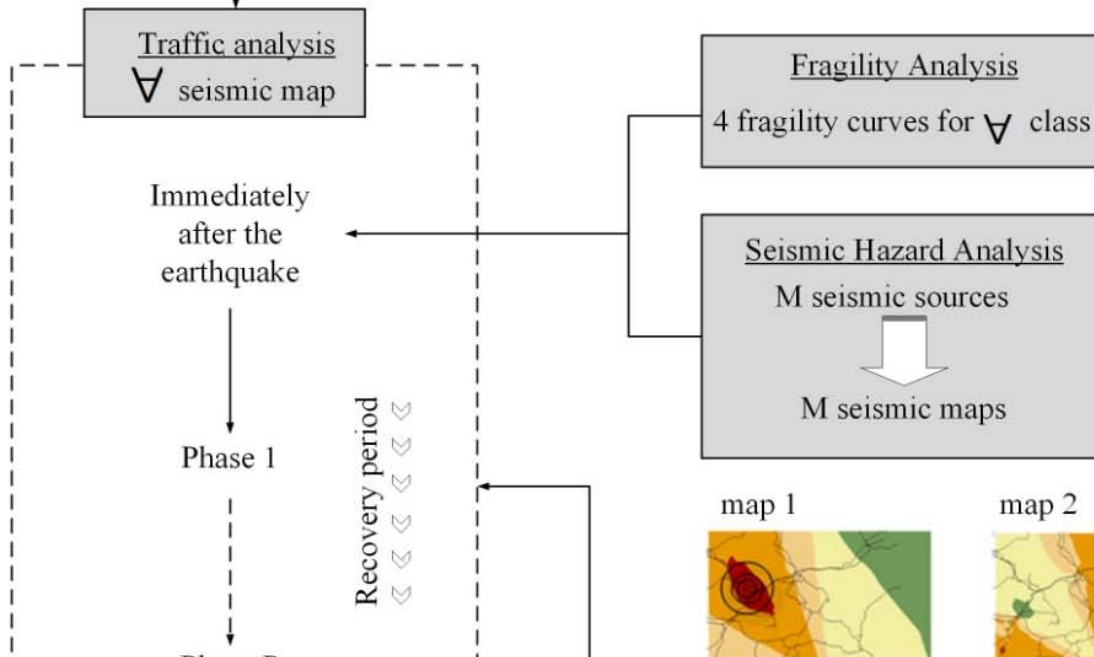
by integrating

vulnerability, seismic hazard, traffic analysis,
consequence analysis & SHM

Network Description



Uncertainty Integration



Case study

InterCity Network for the Prefecture of Western Macedonia, Greece

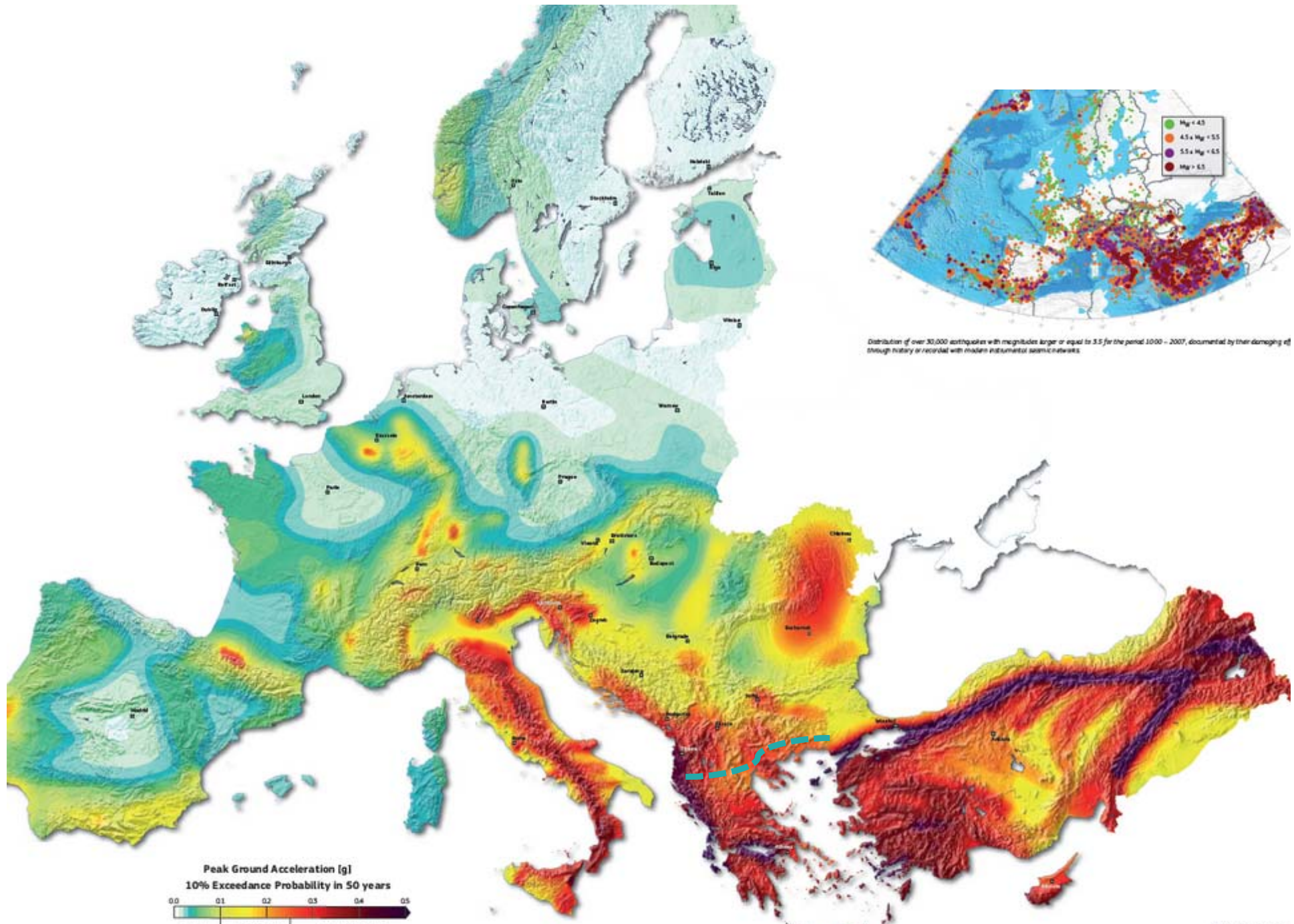
Concept

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Concept

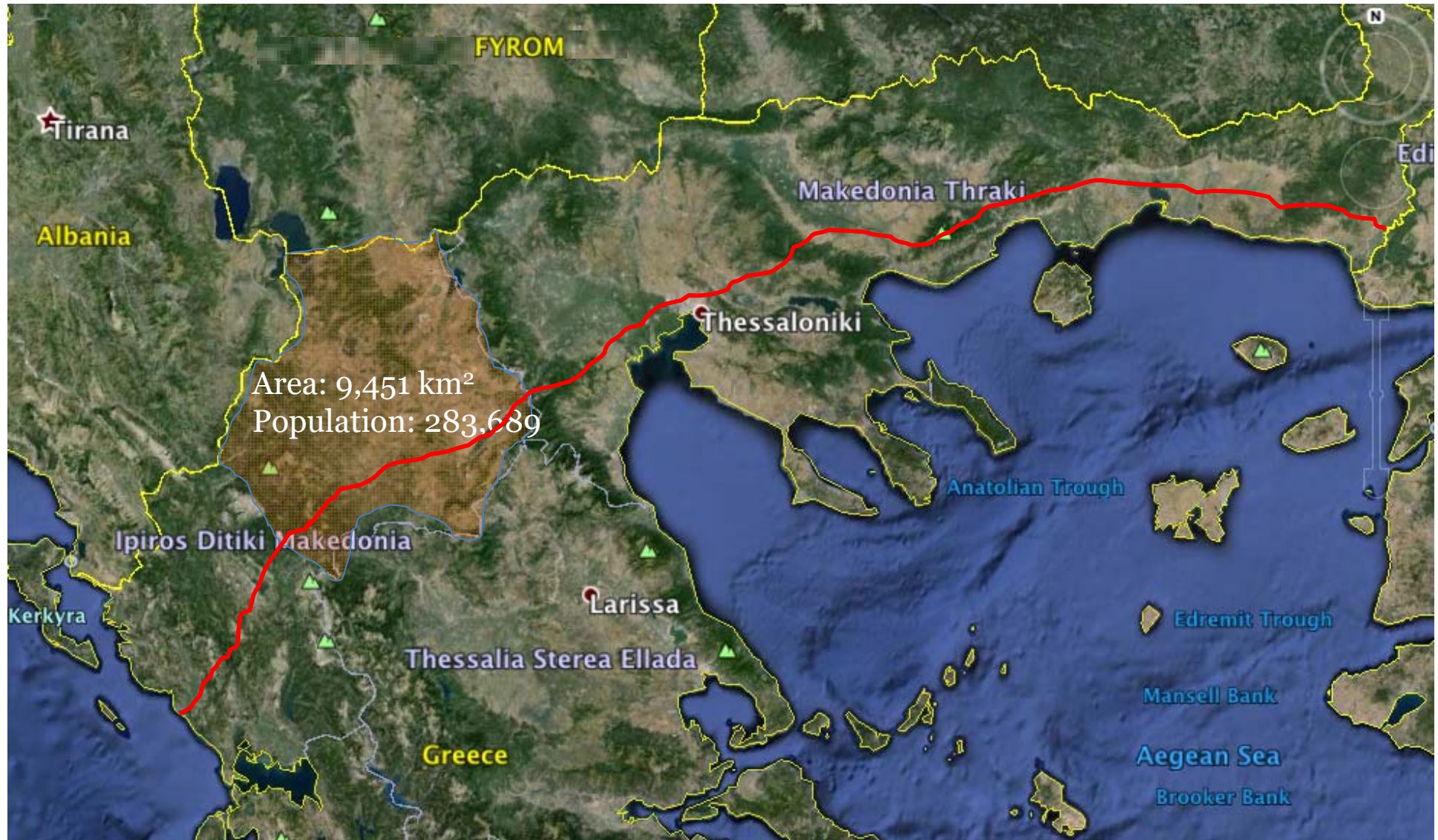
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1. Area of study



Concept

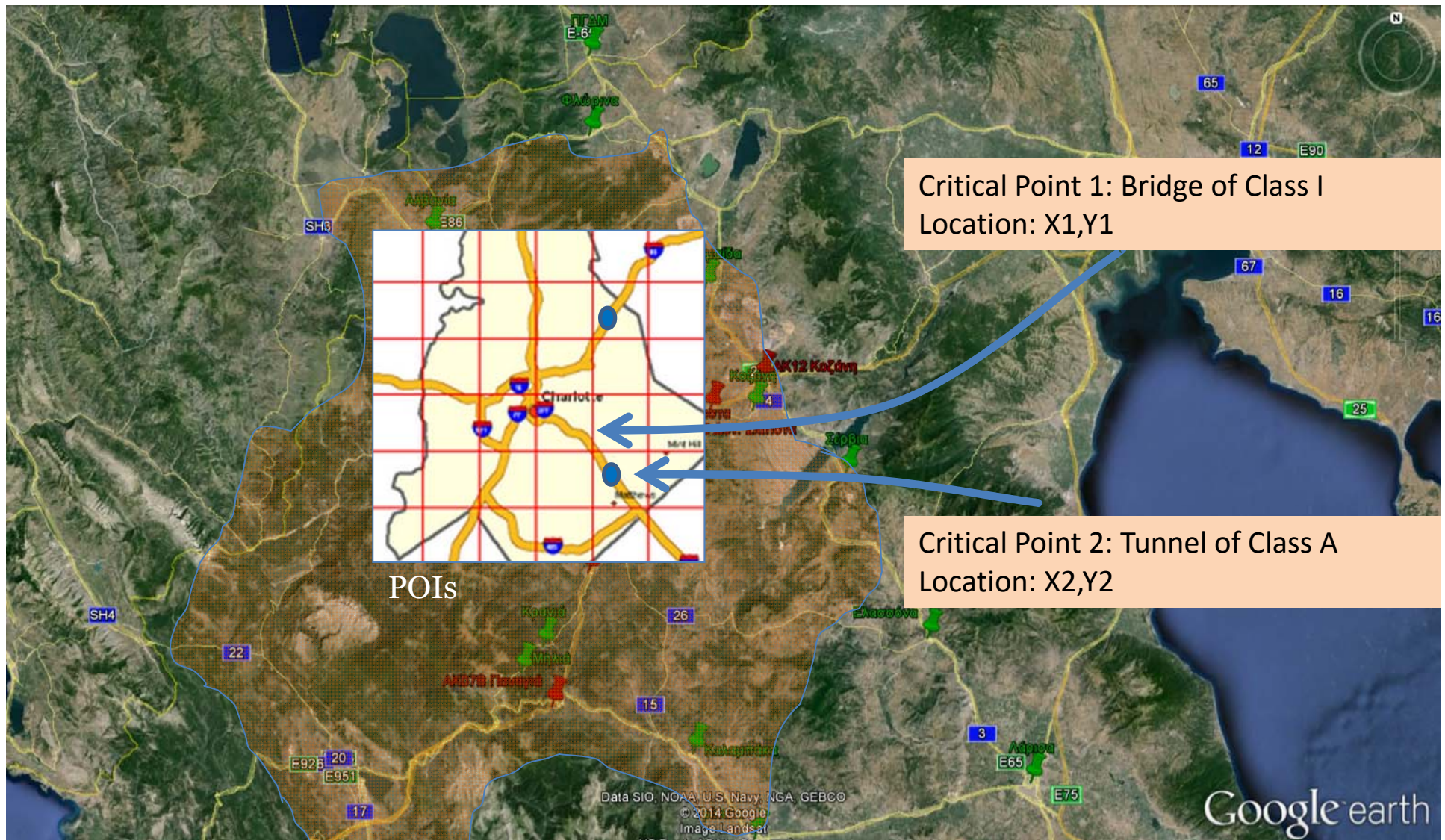
Objectives

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Conclusions

2. Network Grid (portfolio of critical nodes)



Concept

Objectives

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Conclusions

3. Classes of Critical Components

RETISRisk_Step3

3. Definition of network component properties

Input

Total number of network components

74

Import data

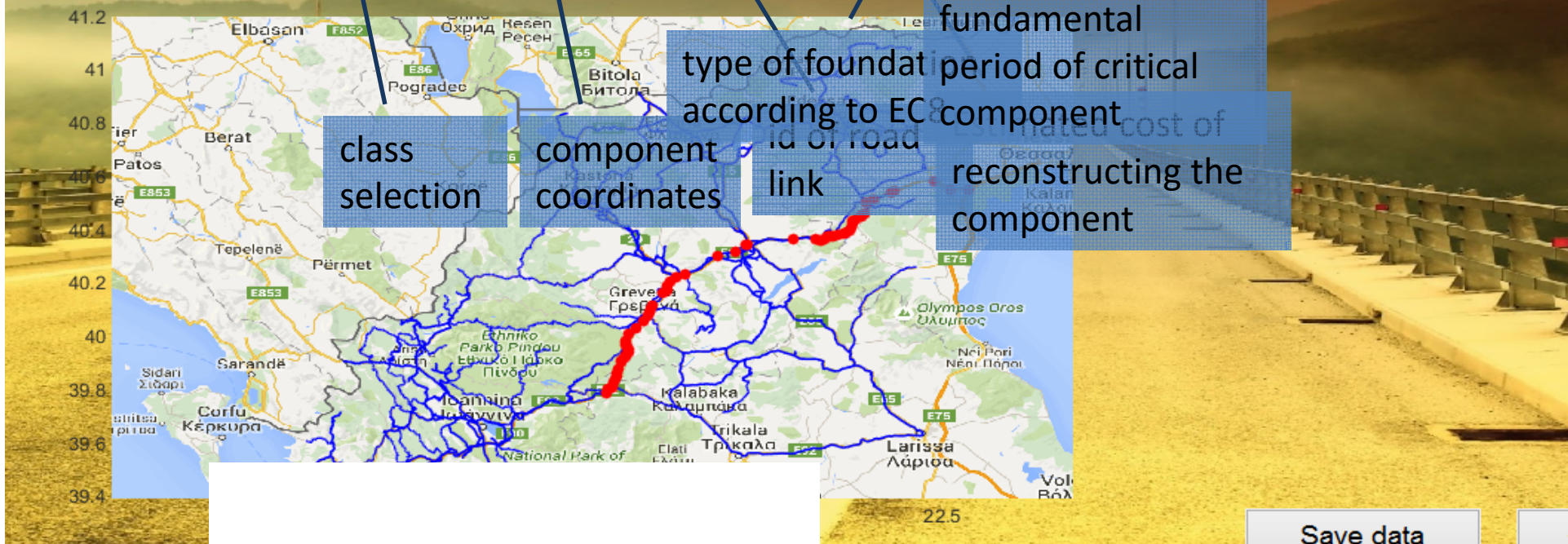
Network component ID	Class	X	Y	Link Id	Reconstruction cost	Soil type	Fundament:
1	1 1	21.3008	39.7911	13	1.13592868...	B	
2	2 2	21.3028	39.7925	3	4.51524023...	B	
3	3 3	21.3211	39.8144	12	1.18304718...	B	

class selection

component coordinates

link

fundamental type of foundat according to EC component reconstructing the component

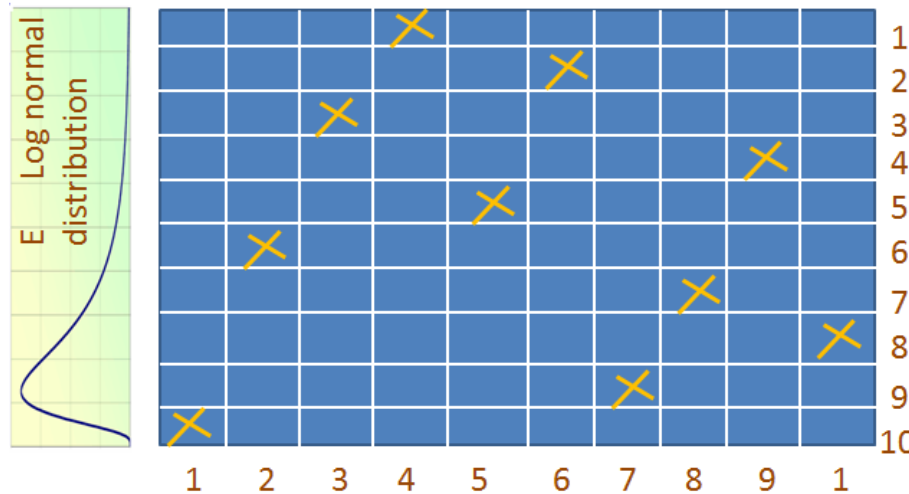


Save data

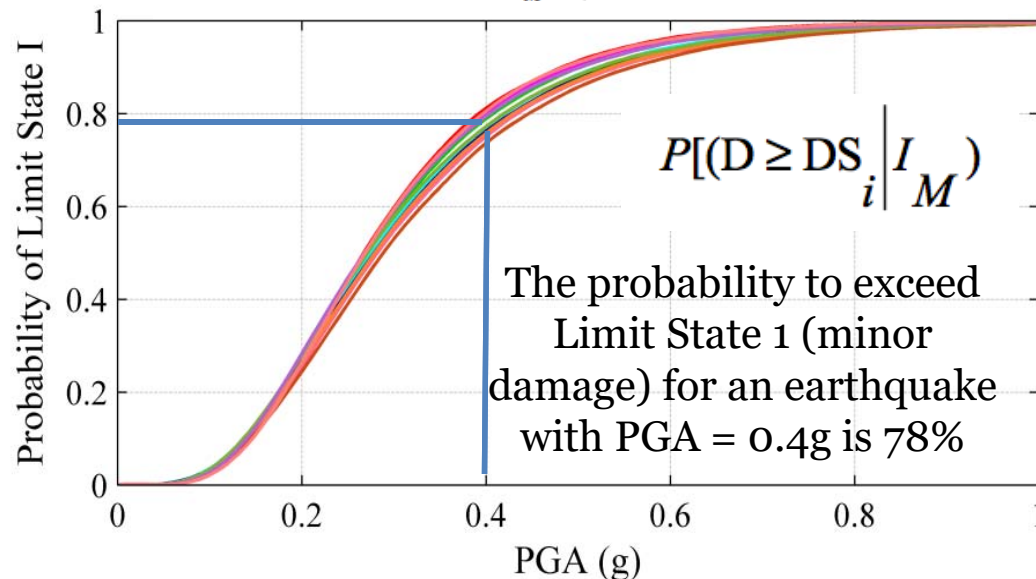
Seismic fragility of bridges within the highway network

$$P[(D \geq DS_i | I_M)$$

4. Vulnerability of each class of structures (1/2)



$$P[D \geq LS | I_M] = \int_{-\infty}^{I_M} \frac{1}{I_M \cdot \sqrt{2\pi \cdot \hat{\beta}}} \cdot e^{\left\{ \frac{[\ln(I_M) \hat{\mu}]^2}{2 \cdot \hat{\beta}^2} \right\}} d(I_M)$$



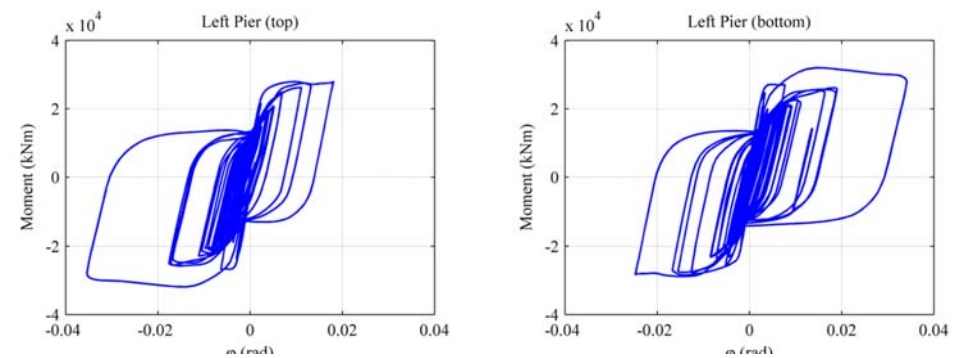
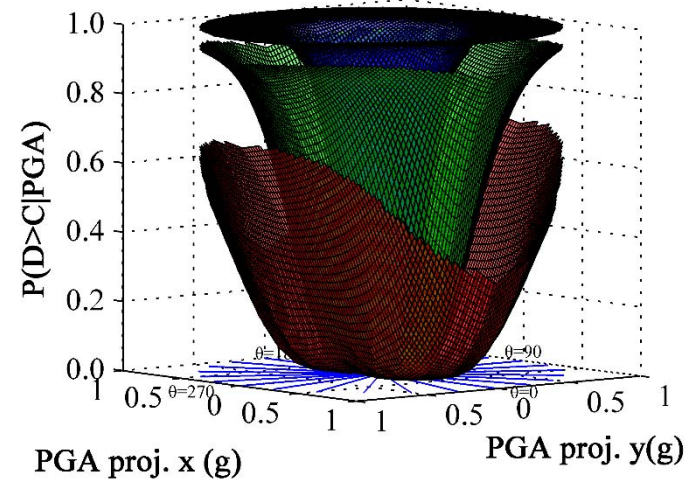
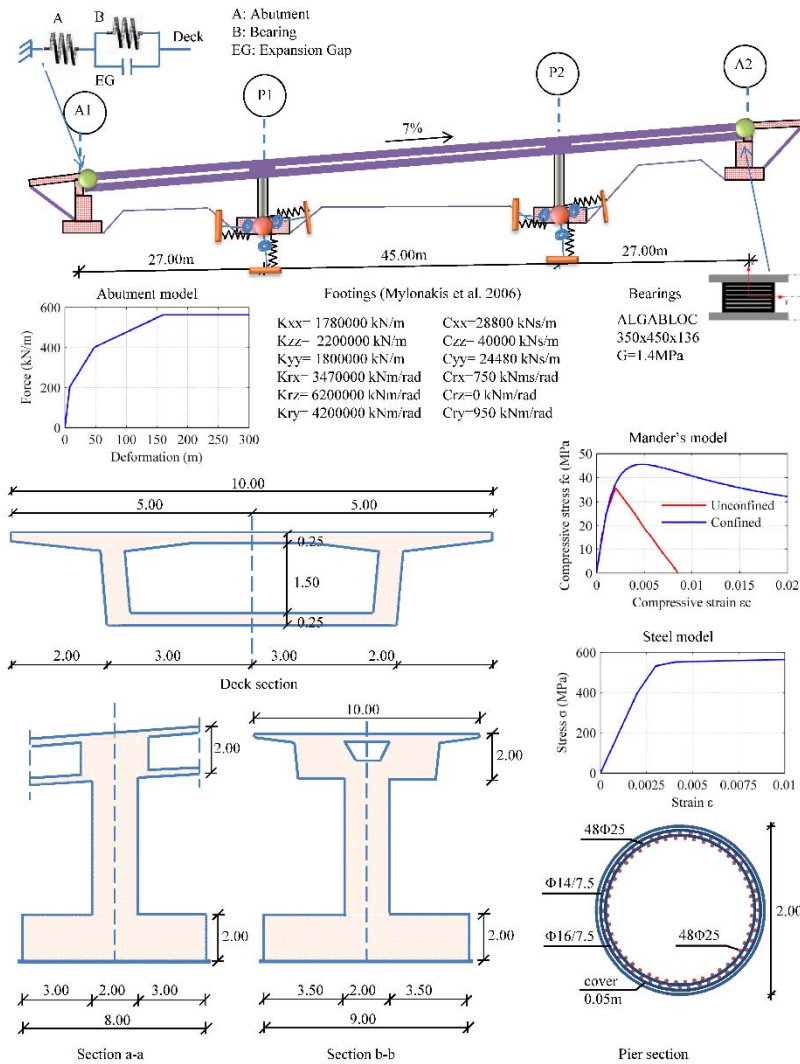
1. For each bridge class
2. Introduce uncertainty in material properties, geometry, finite element modelling, ground motion
3. Generate analysis sample (Monte Carlo, Latin Hypercube sampling)
4. Run series of nonlinear response history analyses
5. Define limit states
6. Compute structural damage proxies
7. Predict the probability of exceeding a given limit state for a given Intensity measure (PGA, Sa(T))

4. Vulnerability of each class of structures (1/2)

Multi-damage Fragility

Limit State	Piers / EDP : d (m)		Abutments	Bearings
	Local	Global	EDP: d (m)	EDP: γ (%)
LS 1 – Minor/Slight damage	$\varphi_1: \varphi_y$	$d_1: \min \begin{cases} d(\varphi_1) \\ d(V_1) \end{cases}$	$d_1 = 1.1 \cdot d_{gap}$ $(\mu_{\varphi, backwall} = 1.5)$	20
LS 2 – Moderate damage	$\varphi_2: \min (\varphi: \varepsilon_c > 0.004, \varphi: \varepsilon_s \geq 0.015)$	$d_2: \min \begin{cases} d(\varphi_2) \\ d(V_2) \end{cases}$	$d_2 = 0.01 \cdot h_{backwall}$	100
LS 3 – Major/Extensive damage	$\varphi_3: \min (\varphi: \varepsilon_c \leq 0.004 + 1.4 \cdot \rho_w \cdot \frac{f_{yw}}{f_{cc}} \varphi: \varepsilon_s \geq 0.06)$	$d_3: \min \begin{cases} d(\varphi_3) \\ d(V_3) \end{cases}$	$d_3 = 0.035 \cdot h_{backwall}$	200
LS 4 – Failure/Collapse	$\varphi_4: \min (\varphi: M < 0.90 \cdot M_{max}, \varphi: \varepsilon_s \geq 0.075)$	$d_4: \min \begin{cases} d(\varphi_4) \\ d(V_4) \end{cases}$	$d_4 = 0.1 \cdot h_{backwall}$	300

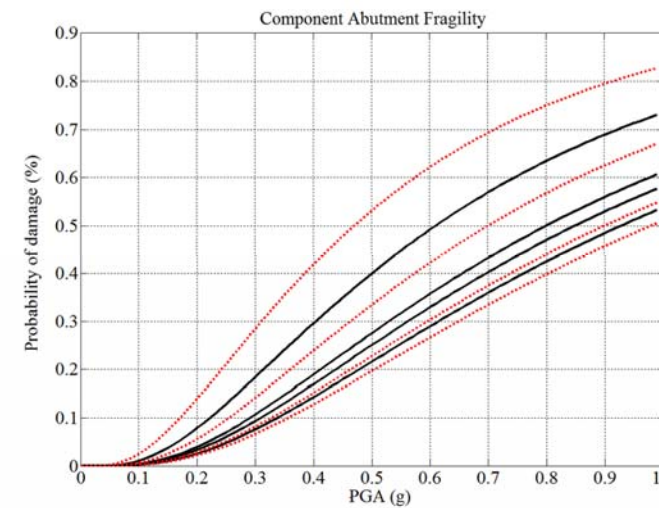
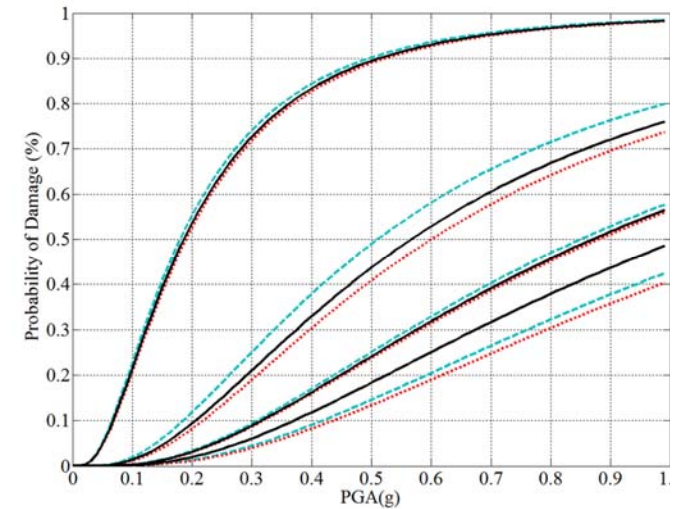
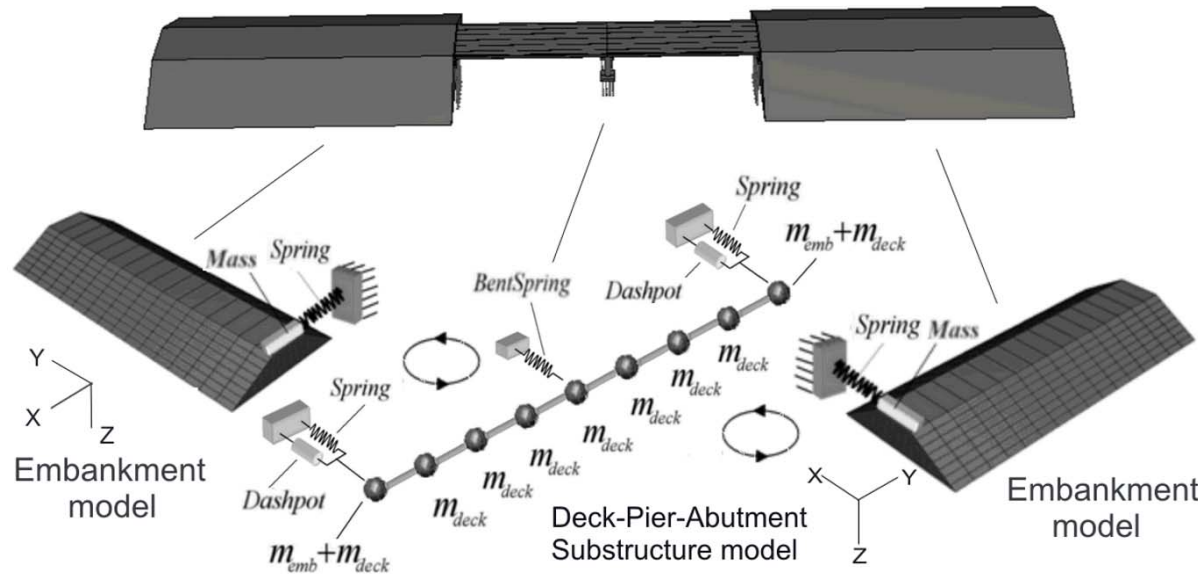
4. Vulnerability of each class of structures (1/2)



$$P_{sys}[D > C | IM] = \frac{\sum_{i=1}^n a_i P_i[C < D | \theta_i]}{\sum_{i=1}^n a_i}$$

Taskari & Sextos (2015)

4. Vulnerability of each class of structures (1/2)



$$M_{emb}^* = B_c \cdot \int_0^{L_c} \int_0^H \rho \cdot \Phi^2(z, y) \cdot dz \cdot dy$$

$$K_{emb}^* = G \cdot B_c \cdot \left(\int_0^{L_c} \int_0^H \Phi(z, y) \cdot \frac{d^2 \Phi(z, y)}{dz^2} \cdot dz \cdot dy + \int_0^{L_c} \int_0^H \Phi(z, y) \cdot \frac{d^2 \Phi(z, y)}{dy^2} \cdot dz \cdot dy \right)$$

$$\mathfrak{S}_{emb}^* = B_c \cdot \int_0^{L_c} \int_0^H \rho \cdot \Phi(z, y) \cdot dz \cdot dy$$

Stefanidou, Sextos. Kappos, Kotsoglou (2016)

Concept

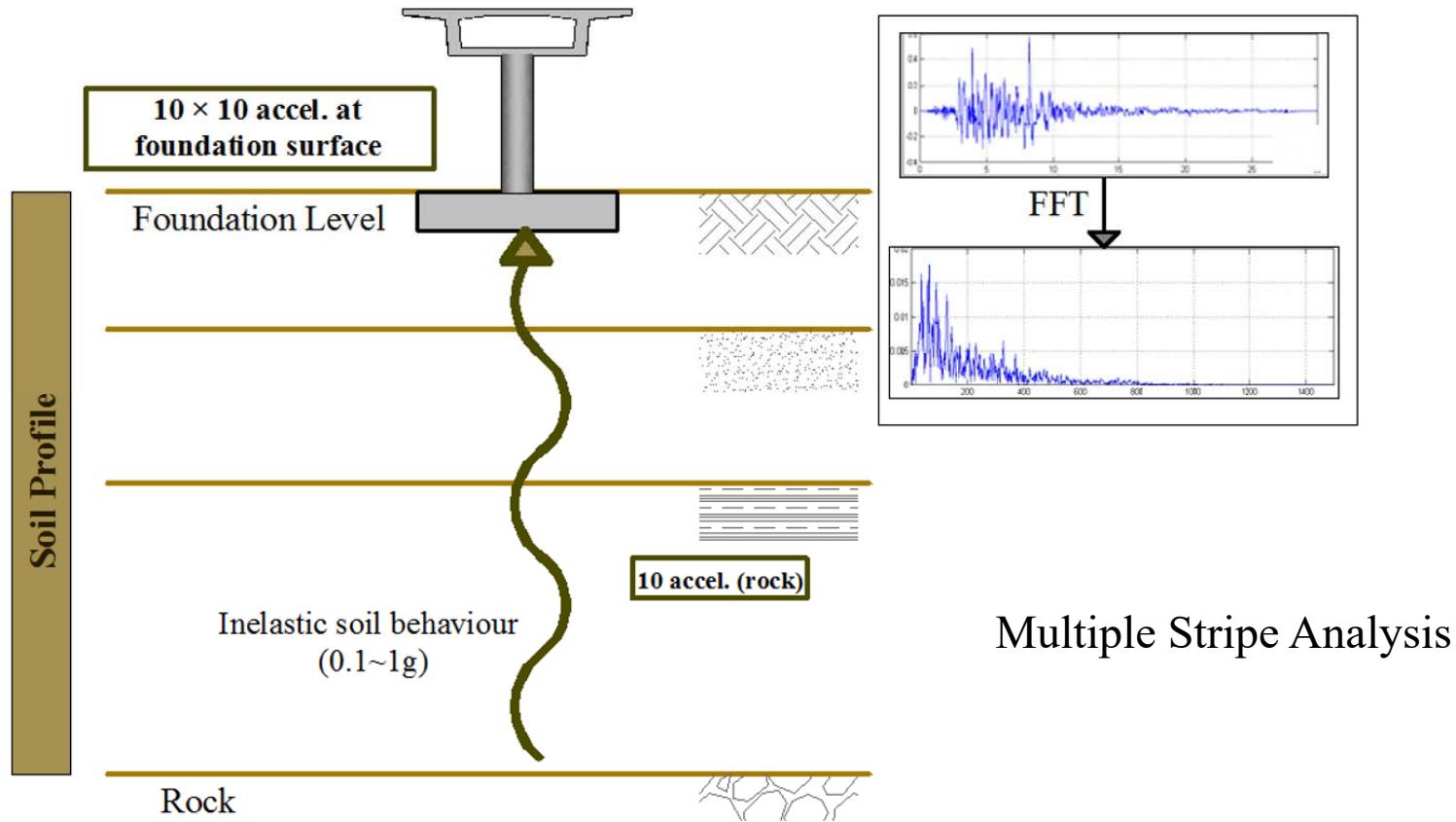
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4. Vulnerability of each class of structures (1/2)



Multiple Stripe Analysis

Sub-set 1 (weak to moderate motions): $0 \leq a_g \leq 0.4g$, $M < 6.5$,

Sub-set 2 (strong, far-field, motions): $0.4 < a_g \leq 0.8g$, $M \geq 6.5$, $R \geq 30\text{km}$,

Sub-set 3 (very strong, near field, motions): $0.8 < a_g \leq 1.0g$, $M \geq 6.5$, $R \leq 30\text{km}$).

4. Vulnerability of each class of structures (2/2)

Input

Class	DS1 IMm	DS1 β	DS2 IMm	DS2 β	DS3 IMm
1	0.0400	0.2500	0.0500	0.2500	0.1000
2	0.0300	0.2500	0.0700	0.2500	0.0900
3	0.0700	0.2700	0.0900	0.2700	0.1200

Figure 3

Class ID: 3

Pr (%)

Sa (g)

DS1 ($\beta = 0.27$)
DS2 ($\beta = 0.27$)
DS3 ($\beta = 0.27$)
DS4 ($\beta = 0.27$)

- Retrieve fragilities from the literature
- User-defined fragility

Help

A set of four fragility curves is used to describe the fragility of every component class. The four fragility curves correspond to minor, moderate, extensive and complete damages (DS 1 to DS4) and can be described by their IMm and β values. "Create fragility curves" is used to calculate the probability of exceeding every damage state for the whole range of the intensity measure values. According to the component classification, a set of fragility curves is assigned to every network component and may be subsequently plotted after selecting the component id using the popup menu.

< Previous Next >

6:58 PM 30/5/2016

5. Vulnerability of each class of tunnels

- Fragility of:
 - i. Tunnels
 - ii. Slopes
- PGA/PGV/PGD as Intensity Measure
- Definition of Limit States



Concept

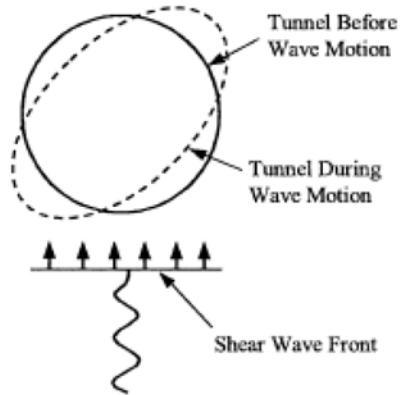
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5. Vulnerability of each class of tunnels



$$\Delta R = \frac{1}{3} \left(\frac{1}{KF \gamma_{\max} d} \right)$$

$$K = \frac{12(1-\nu_s)}{2F + 5 - 6\nu_s}$$

$$F = \frac{2G_s(1-\nu_c^2)R^3}{6E_c I_c}$$

$$\gamma_{\max} = \frac{PGV}{1.7V_s}$$

$$\varepsilon_a = \frac{1}{3} \frac{KG_s \gamma_{\max} tR}{E_c t}$$

$$\varepsilon_b = \frac{1}{6} \frac{KG_s \gamma_{\max} tR^2}{E_c I_c}$$



Limit States

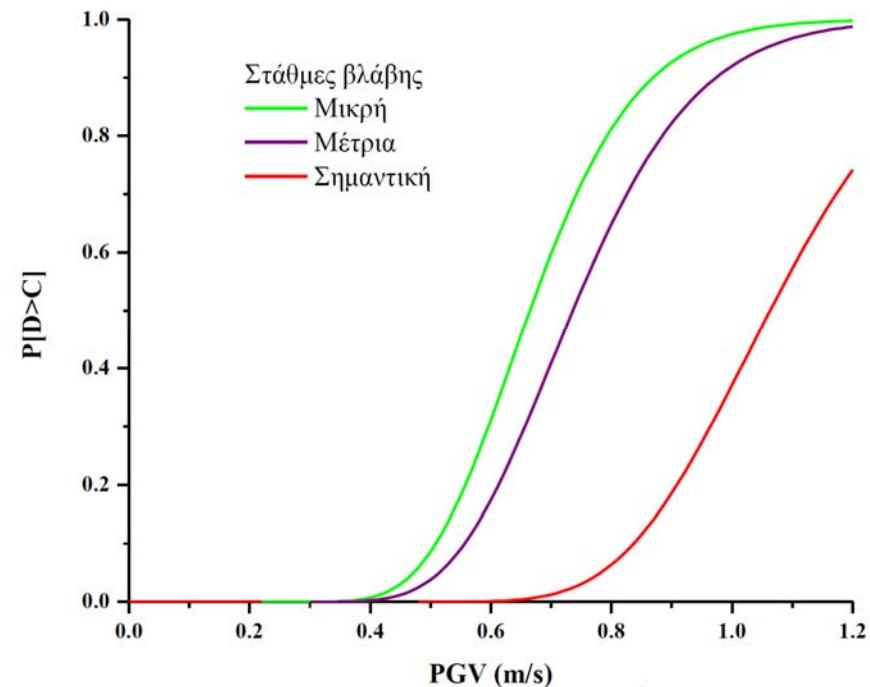
No damage
 $\varepsilon_t / \varepsilon_{c1} < 1.0$

Minor Damage
 $1.0 < \varepsilon_t / \varepsilon_{c1} < 1.30$

Major Damage
 $1.30 < \varepsilon_t / \varepsilon_{c1} < 2.0$

Collapse
 $\varepsilon / \varepsilon_{c1} > 2.0$

Mylonakis, Maravas,
 Taskari, Sextos (2016)



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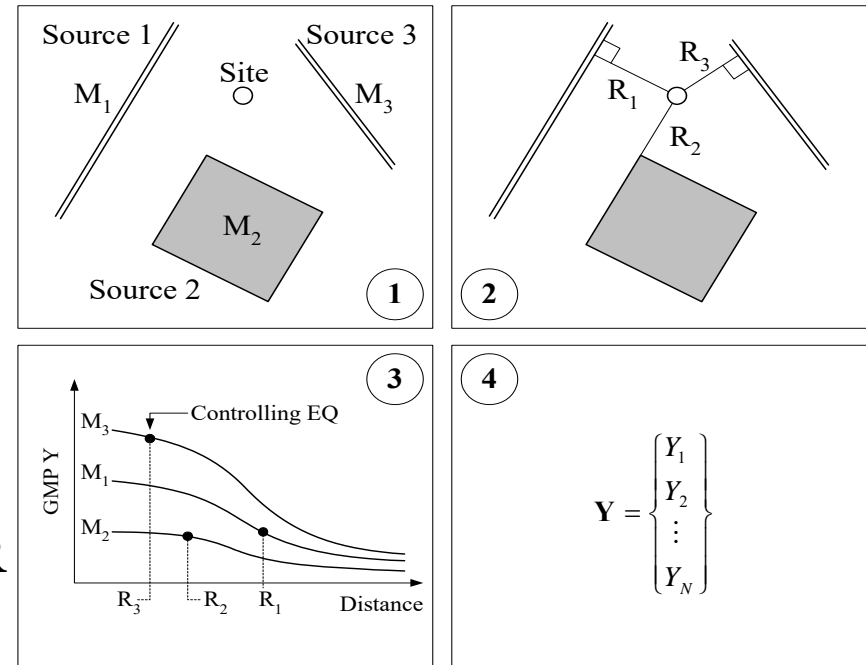
6. Seismic Hazard Assessment

Deterministic : DSHA

Single Magnitude, M
 Single Source-to-site distance, R
 Influence of M,R

Probabilistic : PSHA

Multiple probable Magnitudes, M
 Multiple probable Source-to-site distances, R
 Influence of M,R



$$\lambda_{GM}(gm^*) = \sum_i \left\{ \iiint I[GM > gm^* | m, r, \epsilon] v_i f_{M,R,E}(m, r, \epsilon)_i dm dr d\epsilon \right\} \quad (2.3)$$

$$\underbrace{v_i f_{M,R,E}(m, r, \epsilon)_i}_{\text{how many times per year do all possible levels of ground motion occur from source } i?} = \underbrace{v_i f_M(m | \mathbf{x}_{byp}) f_{\mathbf{x}_{byp}}(\mathbf{x}_{byp})}_{\text{how many times per year does an earthquake of } M=m \text{ occur in source } i \text{ with a hypocentre at } \mathbf{x}_{byp} ?} \underbrace{f_R(r | m, \mathbf{x}_{byp}, \theta_i)}_{\text{when this event occurs, what sort of rupture does it produce?}} \underbrace{f_E(\epsilon)}_{\text{how likely are the possible GM values for this scenario?}}$$

6. Seismic Hazard Assessment

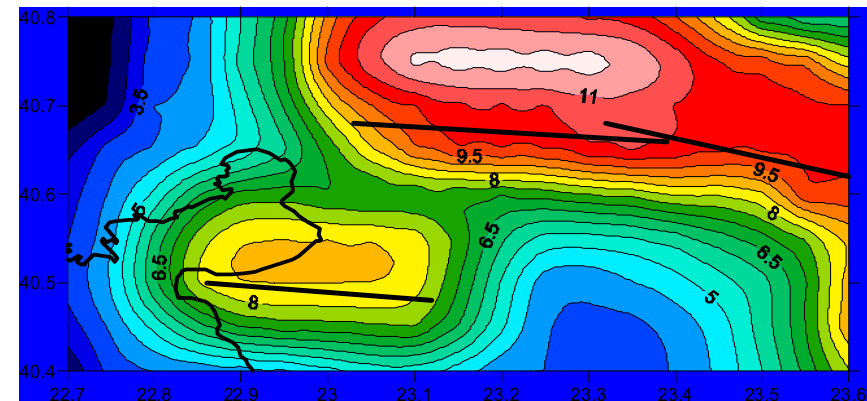
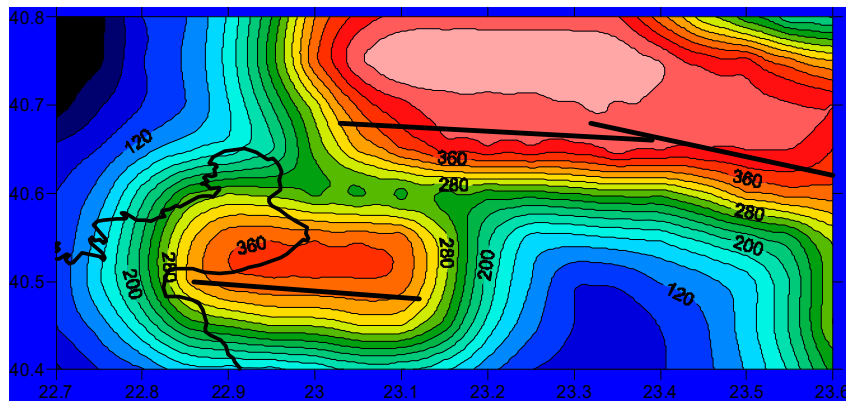
Geographical distribution of expected Intensity Measures

Mean recurrence period: 475 years (V. Margaris & N. Theodoulidis)



PGA (cm/sec²)

PGV (cm/sec)



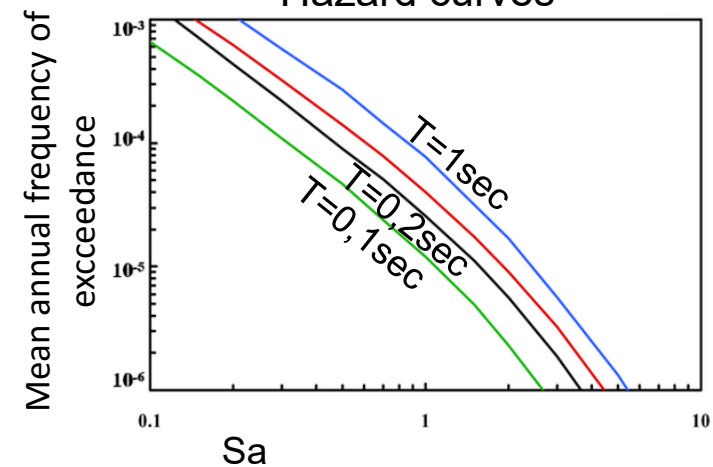
Area Grid



1x1km grid



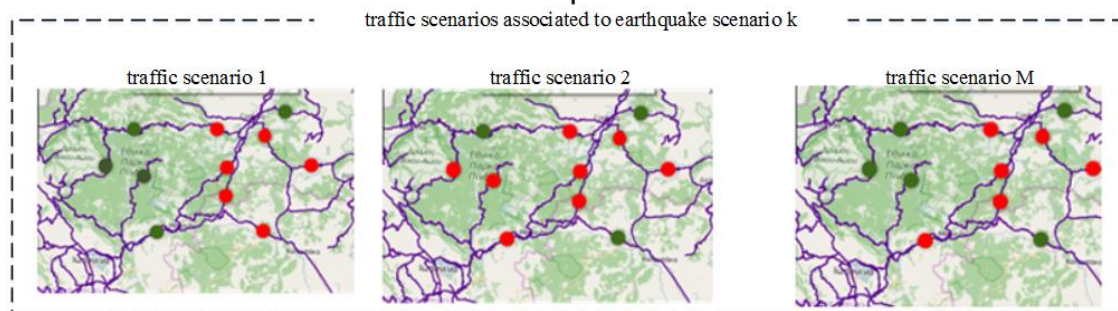
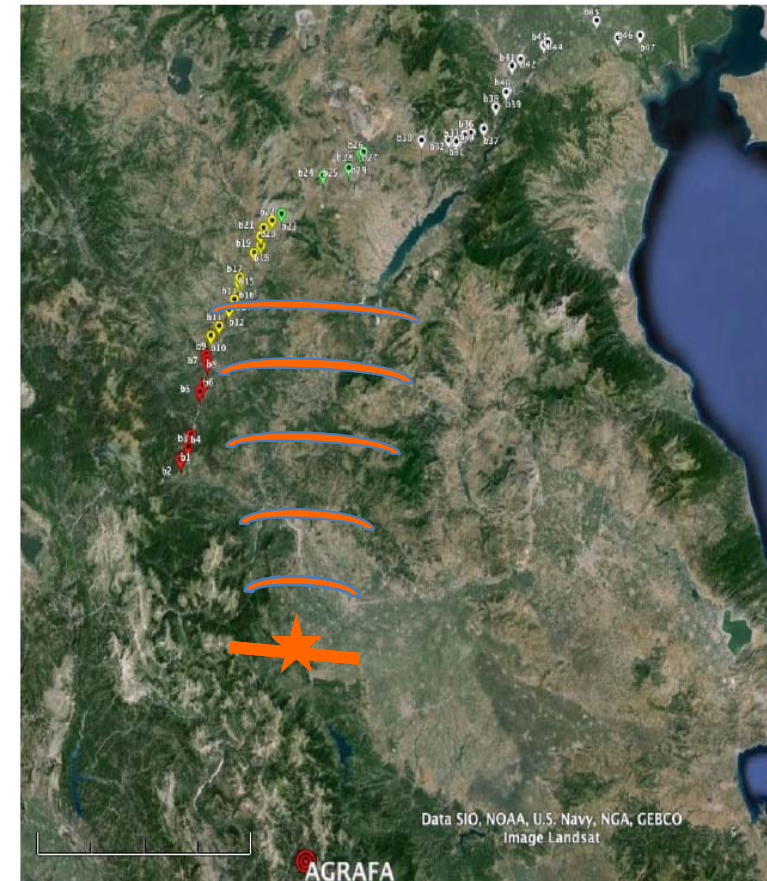
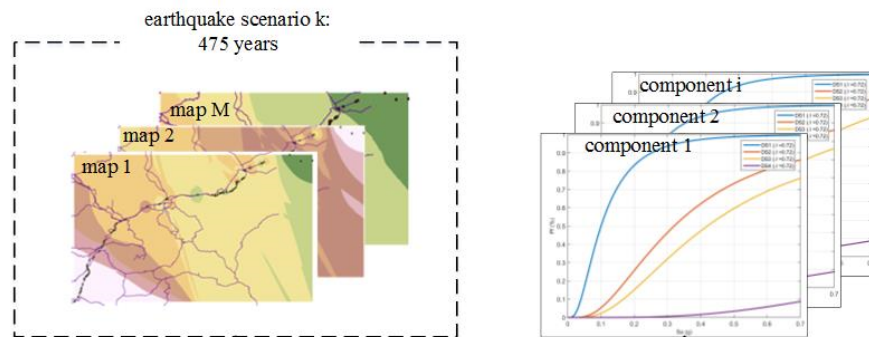
Hazard curves



6. Seismic Hazard Assessment

- k Scenarios (50, 100, 475, 1000)
- m seismic events => m maps of IM
- Functionality of a critical component i

$$\tilde{T}_r = \begin{cases} 1 & \text{if } P_{i,k,m}[D \geq DS_2] | im_{i,k,m} < 0.5 \\ 0 & \text{if } P_{i,k,m}[D \geq DS_2] | im_{i,k,m} \geq 0.5 \end{cases}$$



➔ Traffic flow redistribution given the network components functionality

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7. Traffic analysis

The screenshot displays the NeXTA software interface. On the left, a console window shows the following output:

```
Number of Nodes = 9
Number of Links = 12
Number of Vehicles to be Simulated = 2000
Demand Loading Period = 840 min -> 900 min.
Number of Vehicle Types = 5
Number of Demand Types = 4
[ ] Node
[ ] Link
[ ] Start Traffic Assignment/Simulation...
[ ] Agent based dynamic traffic assignment...
[ ] Zone
[ ] # of Computer Processors = 4
[ ] Conn: start assignment CPU Clock: 00:00:03 --
[ ] OD M: end of network memory allocation.
[ ] Link M: end of network memory allocation.
[ ] Path: end of network memory allocation.
[ ] Subar: end of network memory allocation.
[ ] Sens: ----- Memory allocation completed.-----
[ ] Work: ----- Iteration = 0-----
[ ] Inode: --- agent-based routing and assignment at processor 2
[ ] VMS: --- agent-based routing and assignment at processor 4
[ ] Tol: --- agent-based routing and assignment at processor 1
[ ] Ramp: --- agent-based routing and assignment at processor 3
[ ] Vehid: --- complete assignment CPU Clock: 00:00:03 --
[ ] Trans: --- Network Loading for Iteration 0---
[ ] start simulation process...
[ ] Grid:
[ ] Backg:
simu clock: 14:00,# of veh -- Generated: 0, In network: 0
simu clock: 14:05,# of veh -- Generated: 166, In network: 166
simu clock: 14:10,# of veh -- Generated: 334, In network: 334
simu clock: 14:15,# of veh -- Generated: 500, In network: 500
simu clock: 14:20,# of veh -- Generated: 668, In network: 668
```

The main window shows a map with a network of roads and several red pedestrian icons. A dialog box titled "9. Traffic analysis" is overlaid on the right side of the map. The dialog contains the following text and elements:

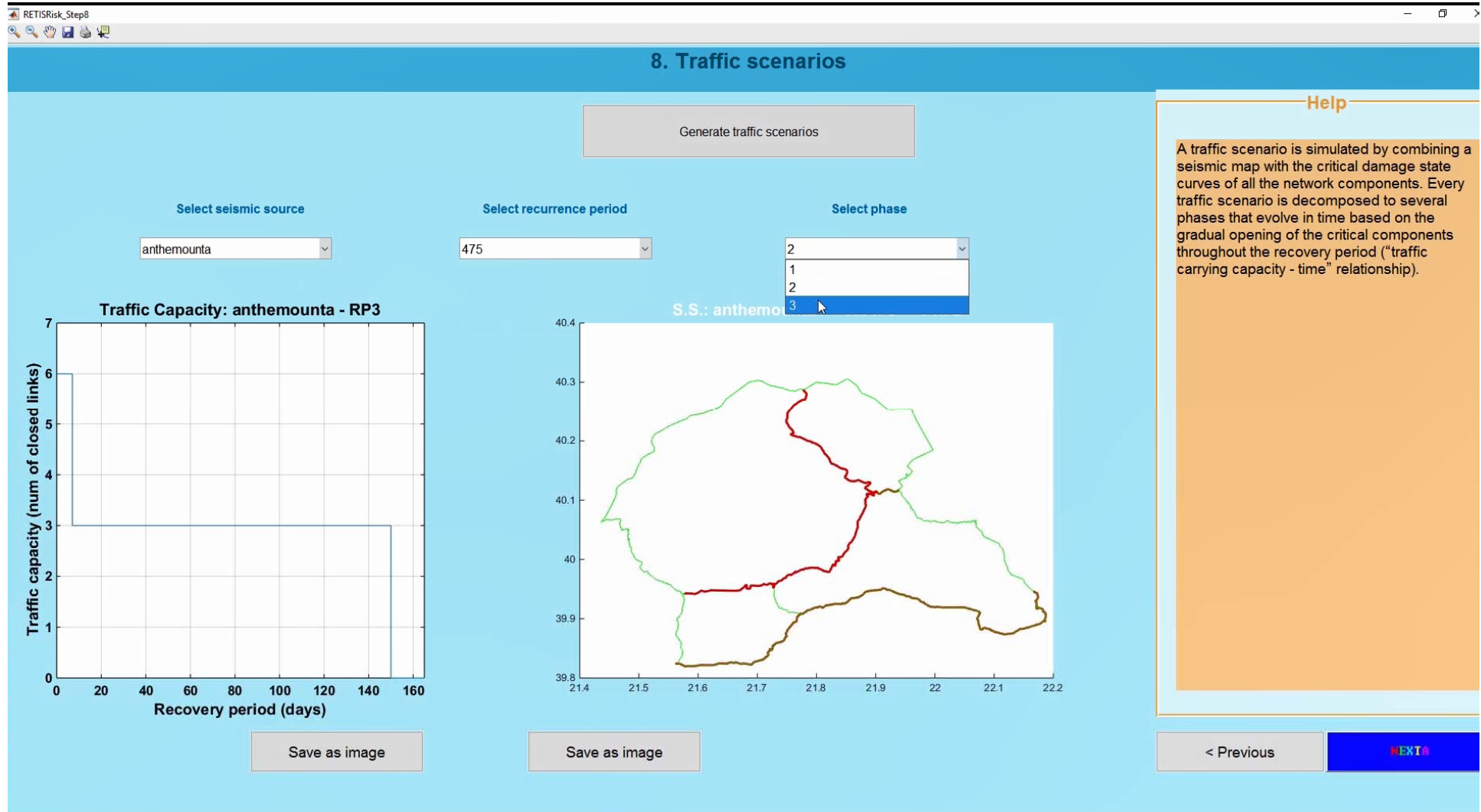
- Text: "Press the 'start' to create the CSV files corresponding to the generated traffic scenarios"
- Diagram: A 3D visualization of a network with arrows pointing to the NEXTA logo.
- Buttons: "START" and "All done!"
- Text: "CSV files have been created. Run NEXTA multiple-scenario analysis and press 'next' after NEXTA output files have been created."
- Navigation: "< Previous" and "Next >" buttons.

At the bottom of the screenshot, the following text is displayed:

K scenarios (50,100, 475, 1000, 2000)
M events (sources, IM spatial distribution)
Monte Carlo with the $P(\text{component } i \text{ to remain open} \mid \text{IM})$

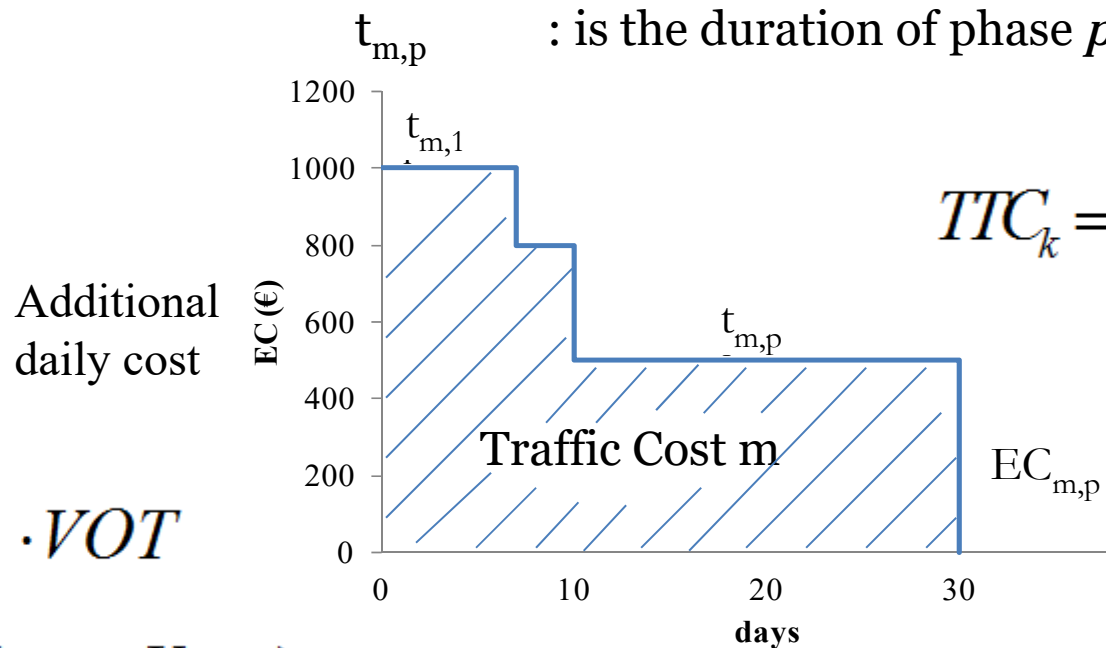
7. Repair cost and restoration vs. time

Traffic capacity over time for each scenario, source and restoration phase
(as closed components gradually return to full function)



8. Total Traffic Cost

$t_{m,p}$: is the duration of phase p of traffic scenario m



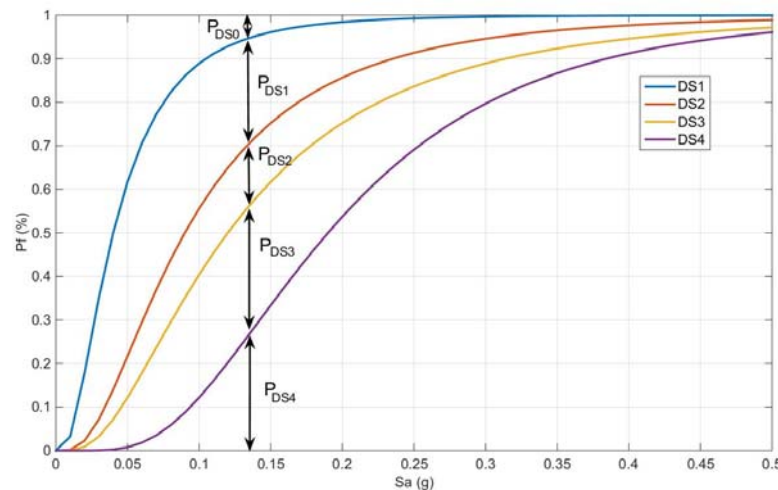
$$TTC_k = \sum_{m=1}^M \sum_{p=1}^P EC_{m,p} \cdot t_{m,p}$$

$$EC_p = D_p \cdot VOT$$

$$D_p = \sum_{j=1} (V_{jp} t_{jp} - V_{j0} t_{j0})$$

- EC_p : additional cost due to traffic conjunction during phase p (per time unit)
- VOT : value of time
- D_p : total delays during phase p
- V_{jp} : traffic load in network link j
- t_{jp} : travel time in network link j
- V_{j0} : traffic load in network link j before earthquake occurrence
- t_{j0} : travel time in network link j before earthquake occurrence

8. Total Structural Cost



DS – Repair Cost Ratio Index

Damage State	Repair-Cost Ratio
No damage	0.00
Slight damage	0.03
Moderate damage	0.25
Major damage	0.75
Complete damage	1.00

Structural Cost for critical component i :

$$D_i = \sum_1^M (RCR_1^i * P_{DS1}^i + RCR_2^i * P_{DS2}^i + RCR_3^i * P_{DS3}^i + RCR_4^i * P_{DS4}^i) * TCC_i$$

M : total number of the identified earthquake sources

TCC_i : total construction cost of component i

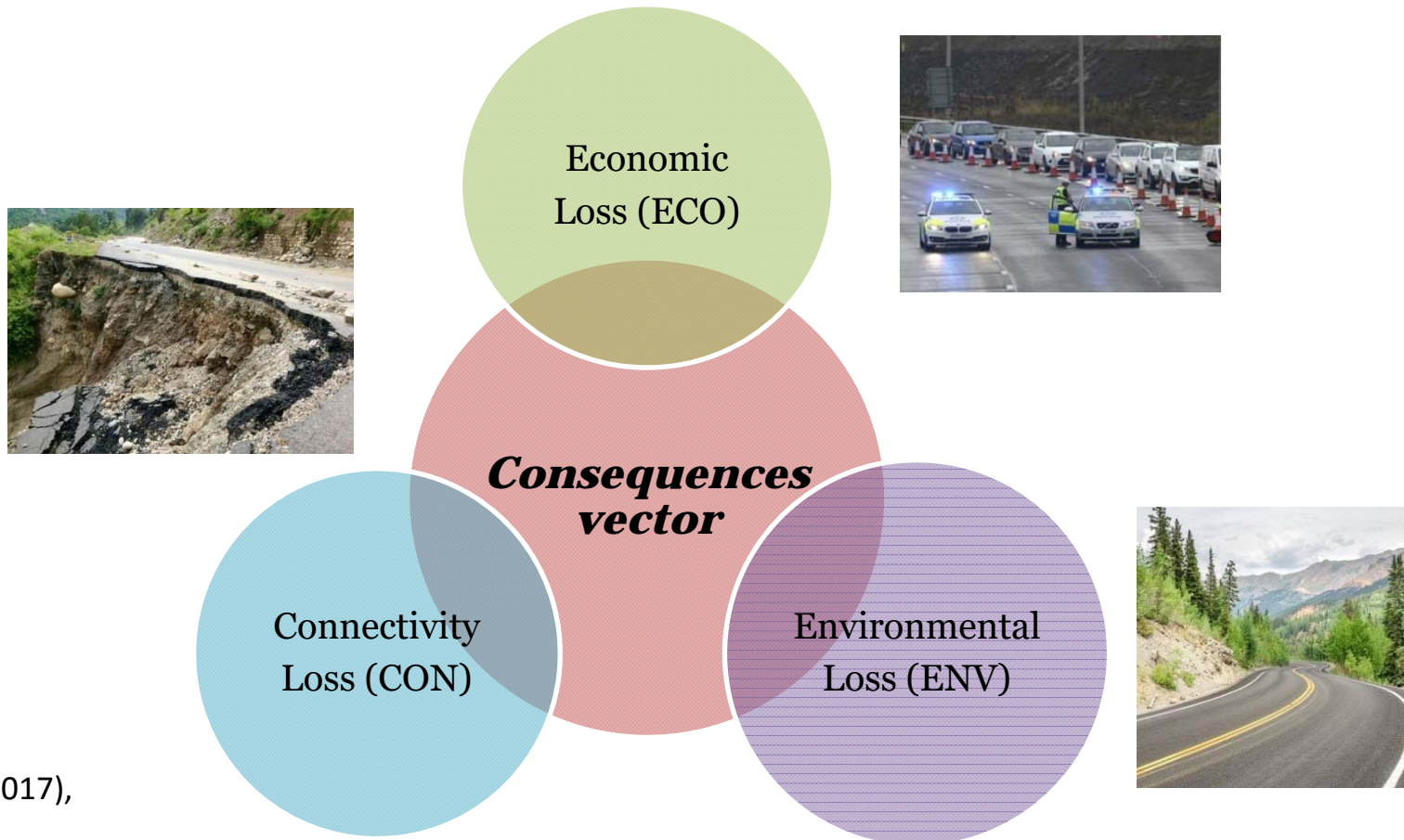
Total (for the entire network) Structural Cost :

$$TSC_k = \sum_{i=1}^N D_{i,k}$$

N : total number of critical network components

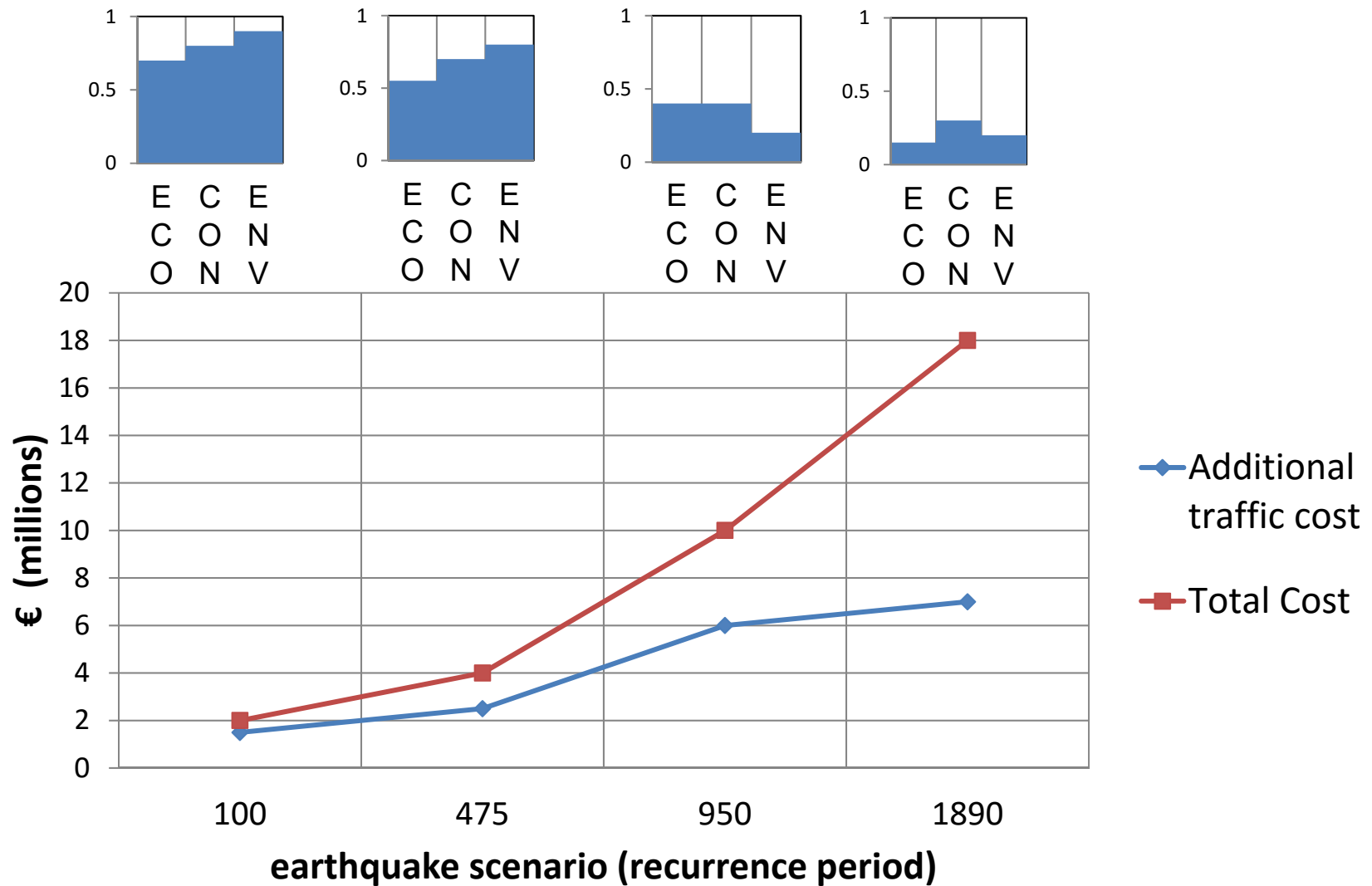
9. Consequence analysis

- assessment of losses that are not easily quantified in monetary units
- values ranging from 0 to 1 (lower indicator values imply higher losses)

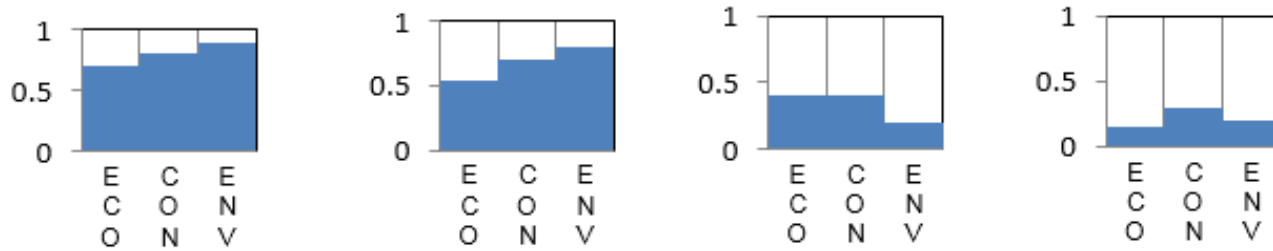


Sextos et al. (2017),
16WCEE, Chile

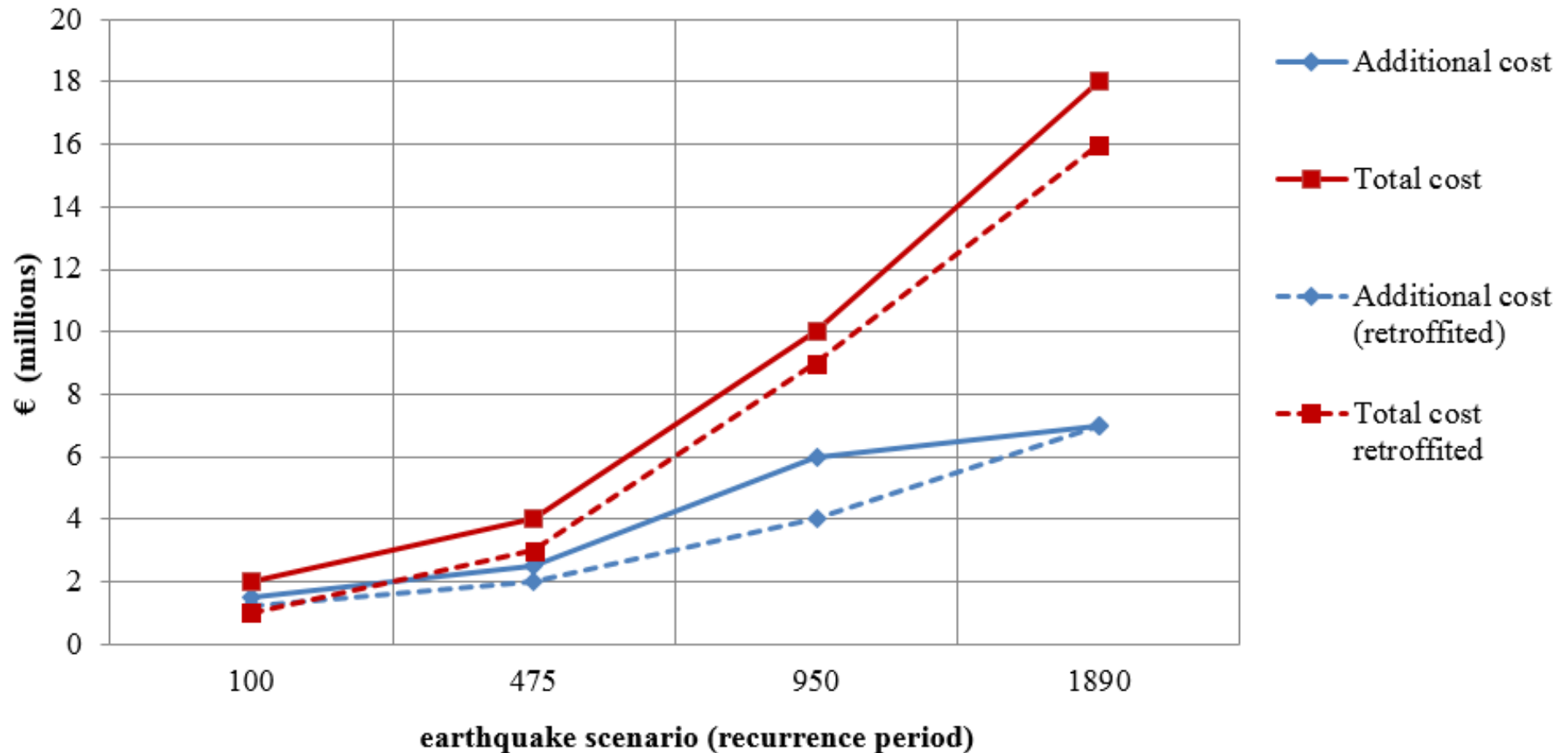
10. Decision making



10. Decision making



To retrofit or not?



Concept

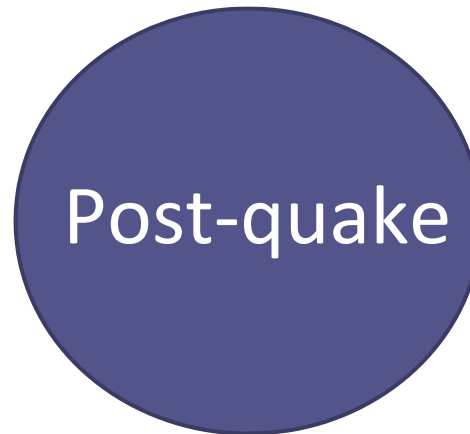
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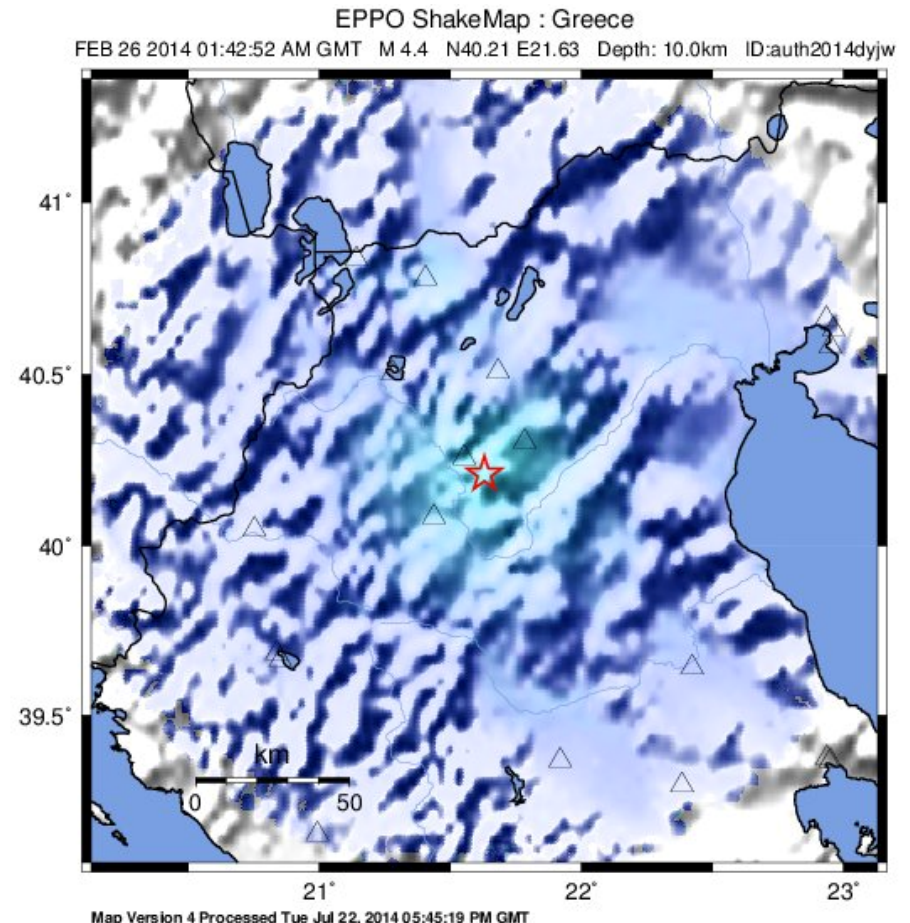
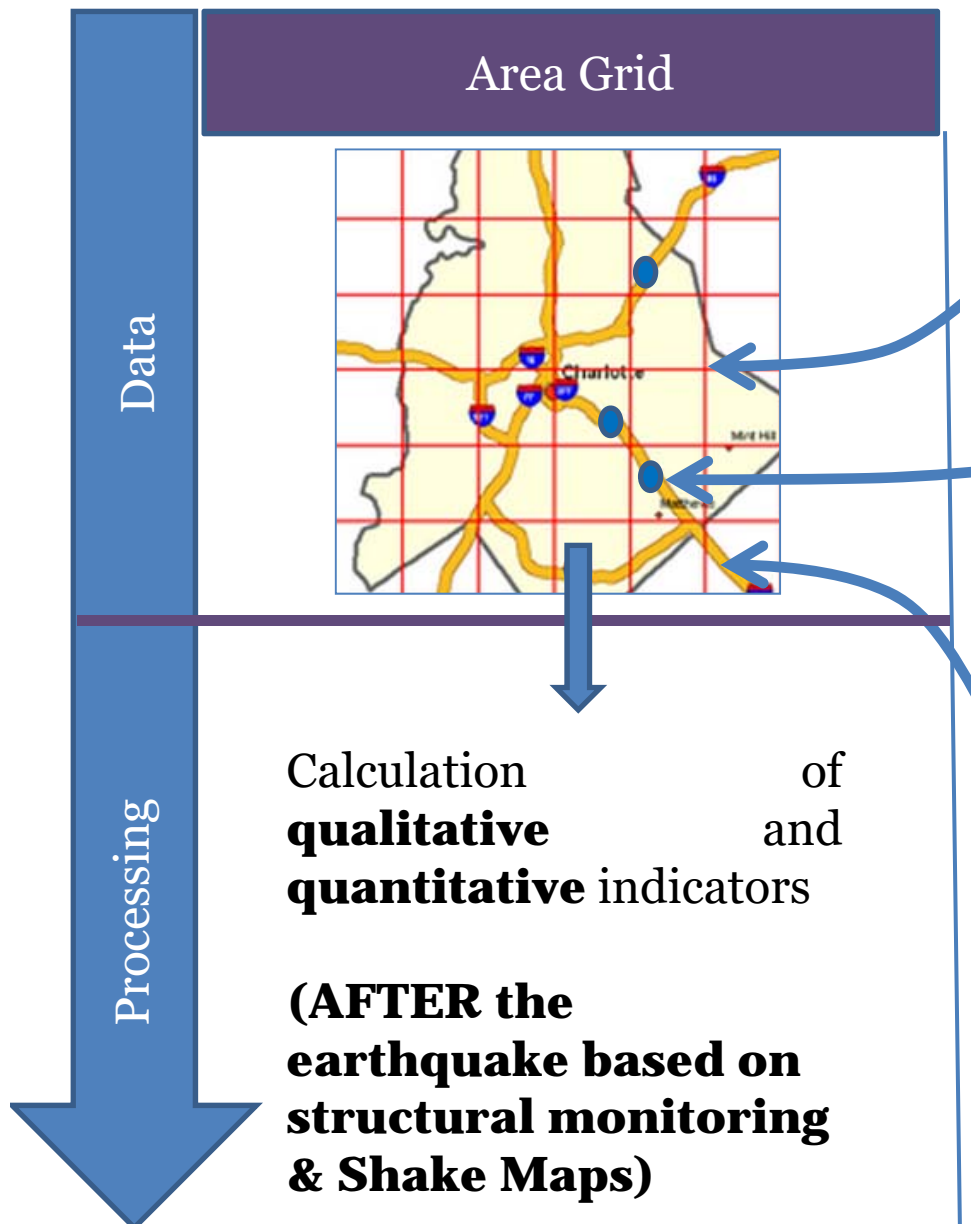
Conclusions

SHM and (nearly) Real-time Seismic Risk Assessment



Minimize implications on disaster
response (immediate after) and
recovery (in the long term)

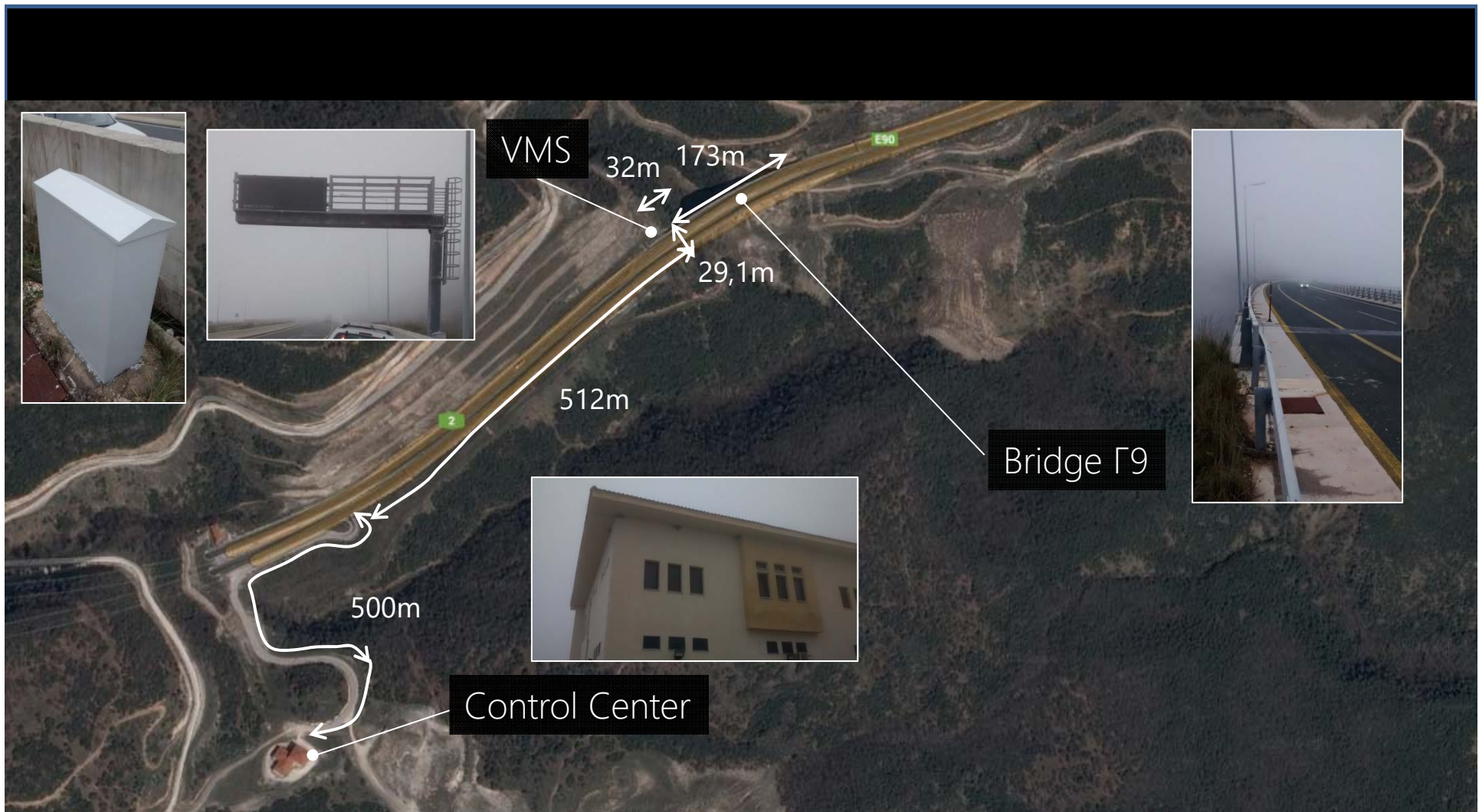
Update with actual IM



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

Update with actual Sa(T)



G. Sergiadis et. al (2016)

Concept

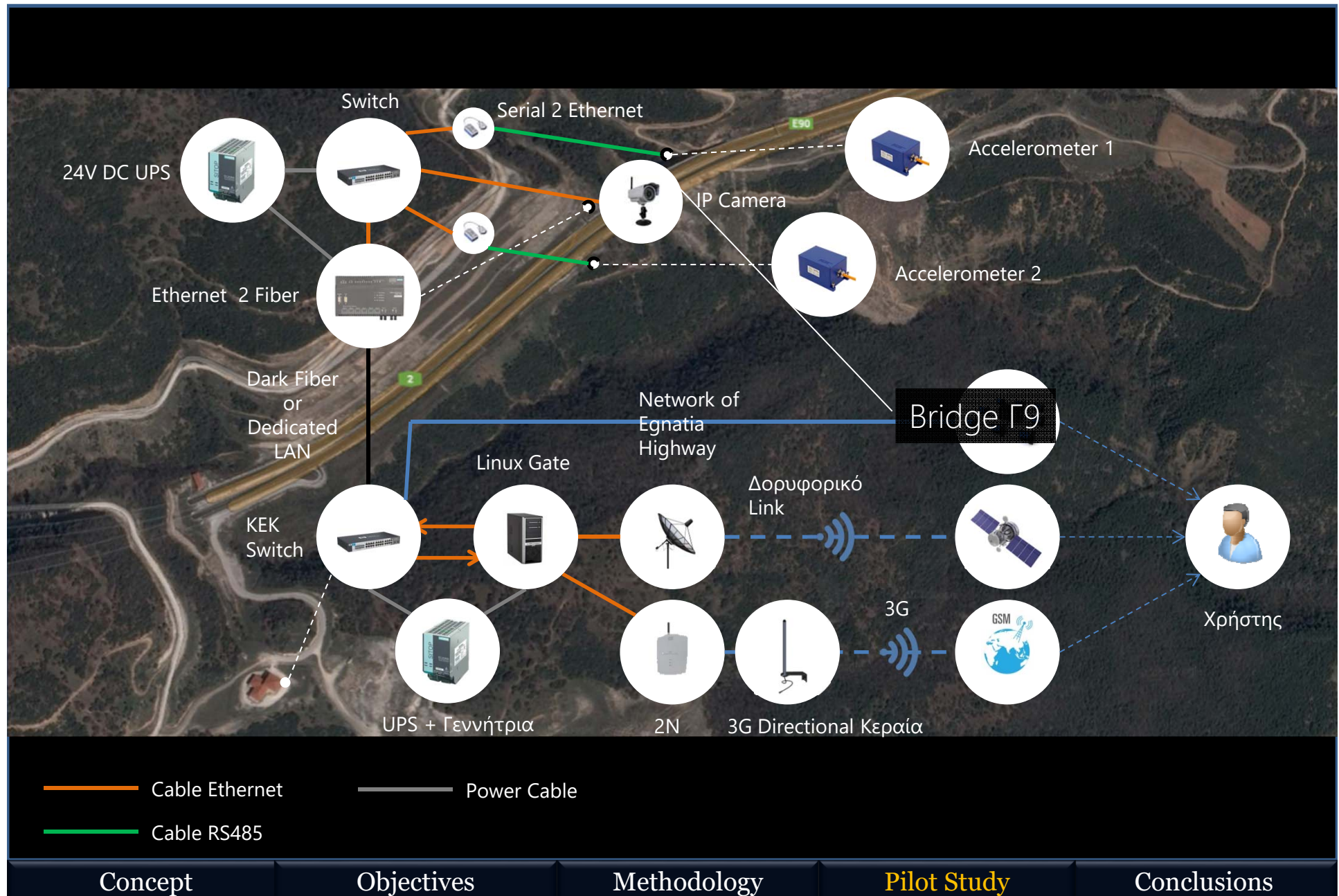
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Update with actual Sa(T): Satellite link





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Conclusions

- ❑ A novel, modular methodology for the assessment of Seismic Risk in Intercity Highway Networks was developed
- ❑ Methodology and web-based software are parametrically structured and are open to be used in different European Areas
- ❑ Modular structure permits incorporation of natural or man-made hazards as well as additional network components


Acknowledgements: Yiannis Kilanitis, Ph.D. student, Aristotle University



www.retis-risk.eu - Home

www.retis-risk.eu

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Retis-risk

Real Time Intercity Seismic Risk
seismic risk in urban and interurban road networks.

1,700

Km road

46

bridges and

28

tunnels

182

km of tunnels

75

km of bridges

www.retis-risk.eu

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