Anastasios Sextos

Associate Professor

University of Bristol

Aristotle University Thessaloniki

Resilience-based Seismic Design

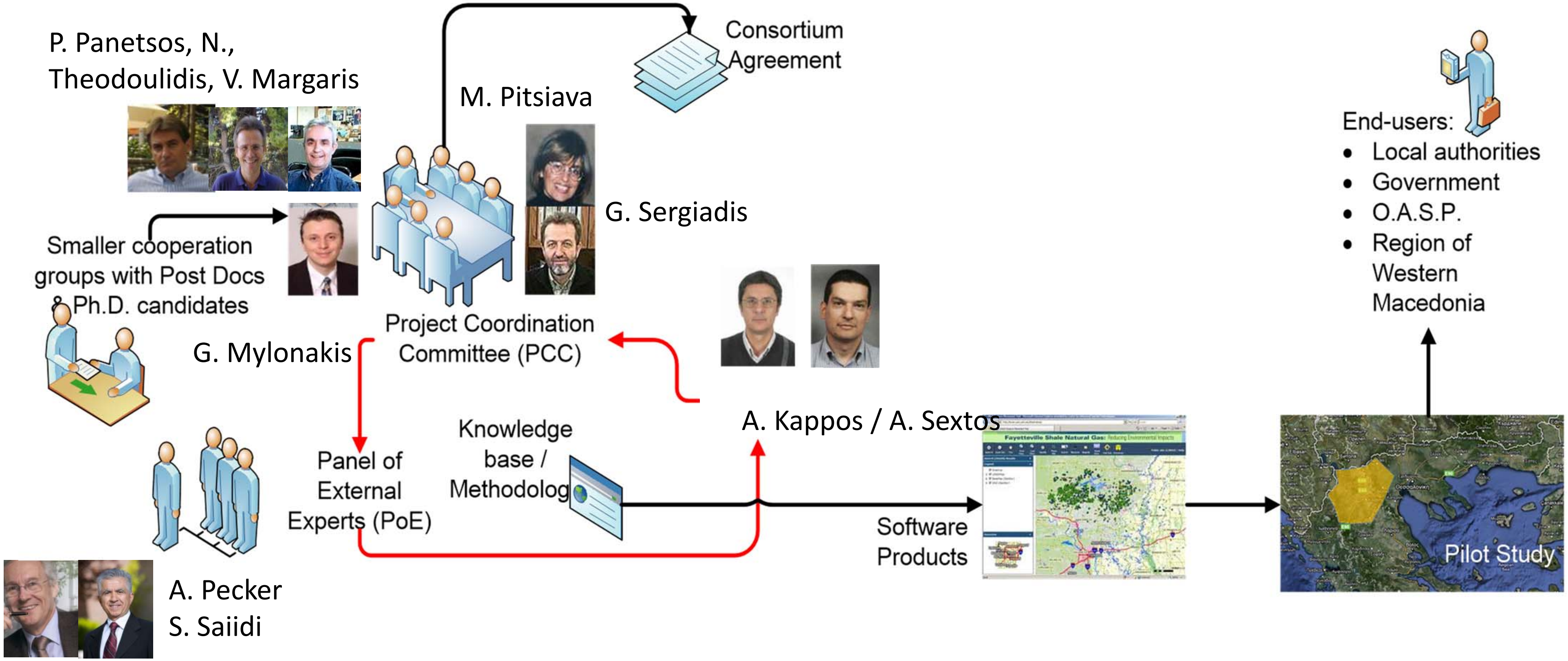
Wider Performance Criteria

Pre-quake & Post-quake

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



Objective

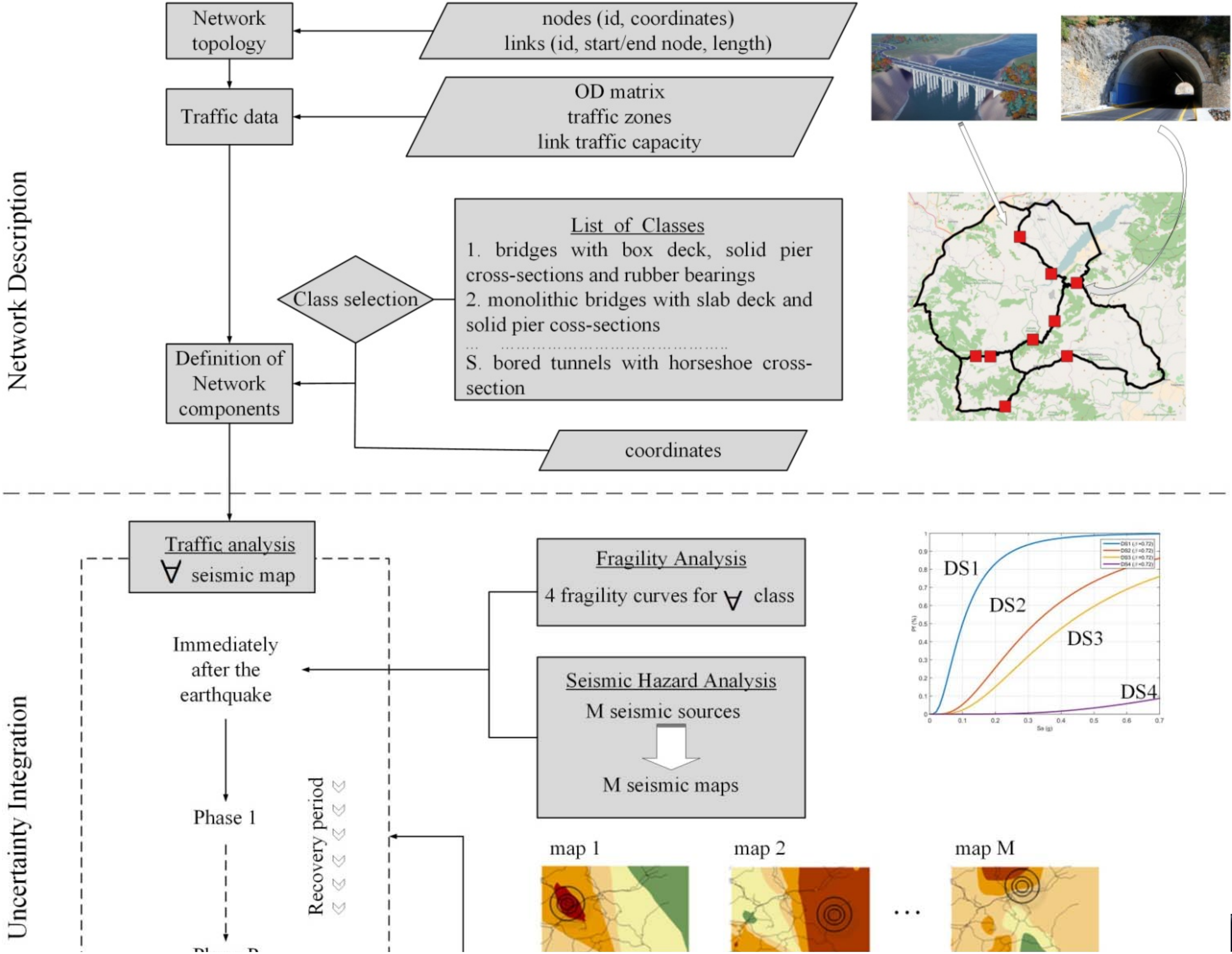
Risk-informed Decision Making of Highway Networks

for

State & Stakeholders

by integrating

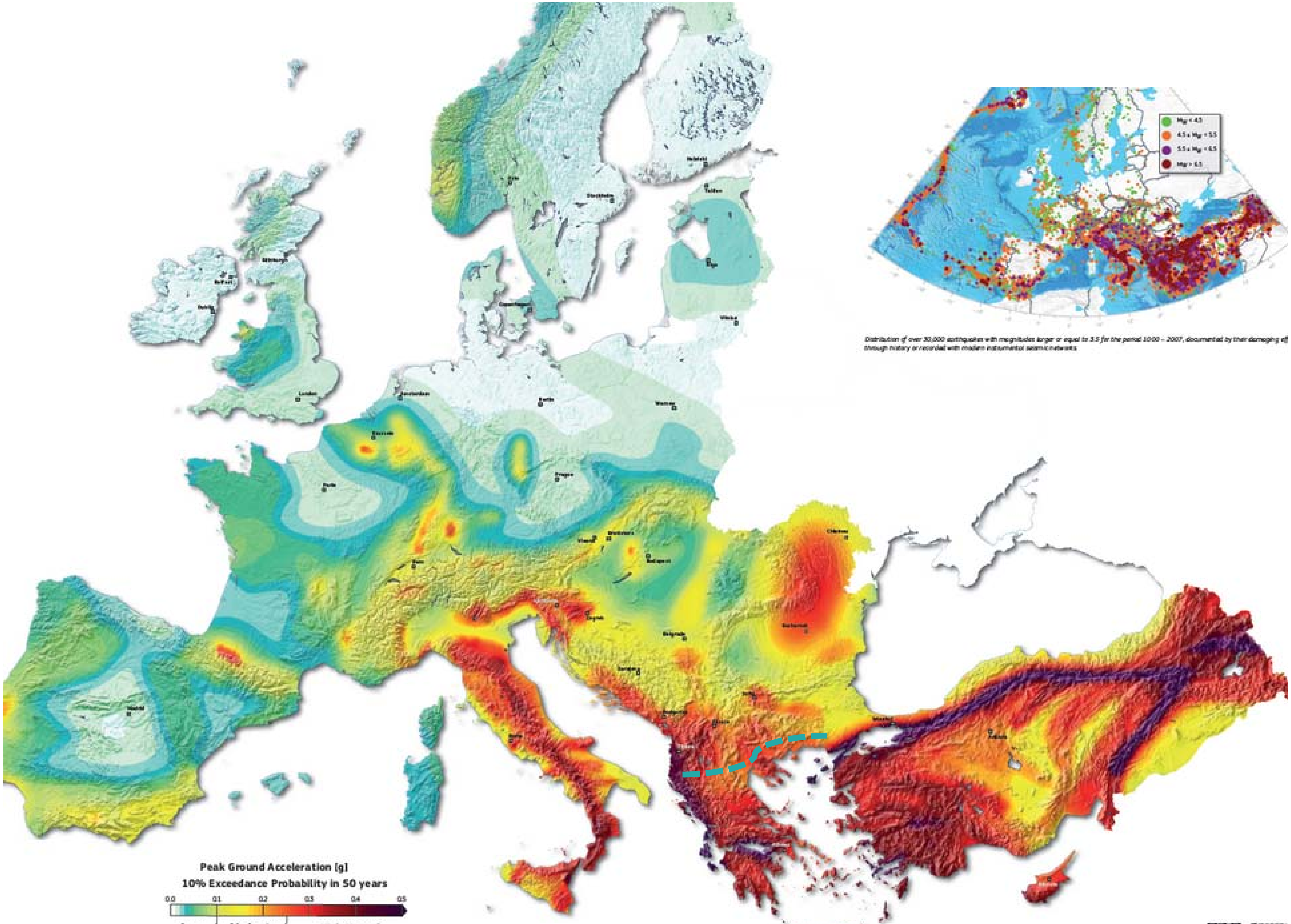
vulnerability, seismic hazard, traffic analysis,
consequence analysis & SHM



Network Description
Network topology
nodes (id, coordinates)
links (id, start/end node, length)
Traffic data
OD matrix
traffic zones
link traffic capacity
List of Classes
1. bridges with box deck, solid pier cross-sections and rubber bearings
2. monolithic bridges with slab deck and solid pier coss-sections
...
S. bored tunnels with horseshoe cross-section
Class selection
Definition of Network components
coordinates
Uncertainty Integration
Traffic analysis
∀ seismic map
Immediately after the earthquake
Phase 1
Recovery period
Fragility Analysis
4 fragility curves for ∀ class
Seismic Hazard Analysis
M seismic sources
M seismic maps
DS1
DS2
DS3
DS4
map 1
map 2
...
map M

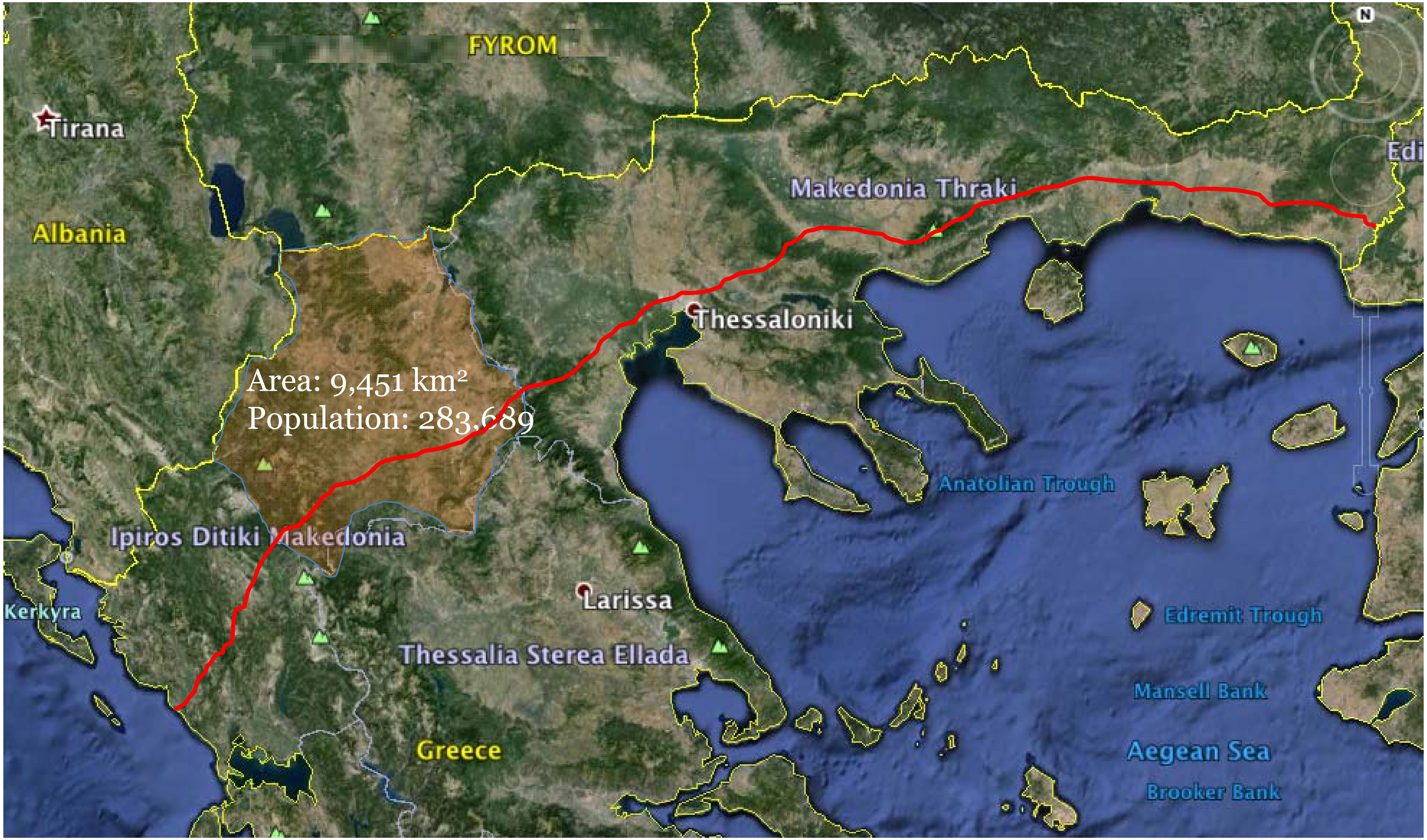
Case study

InterCity Network for the Prefecture of Western Macedonia, Greece

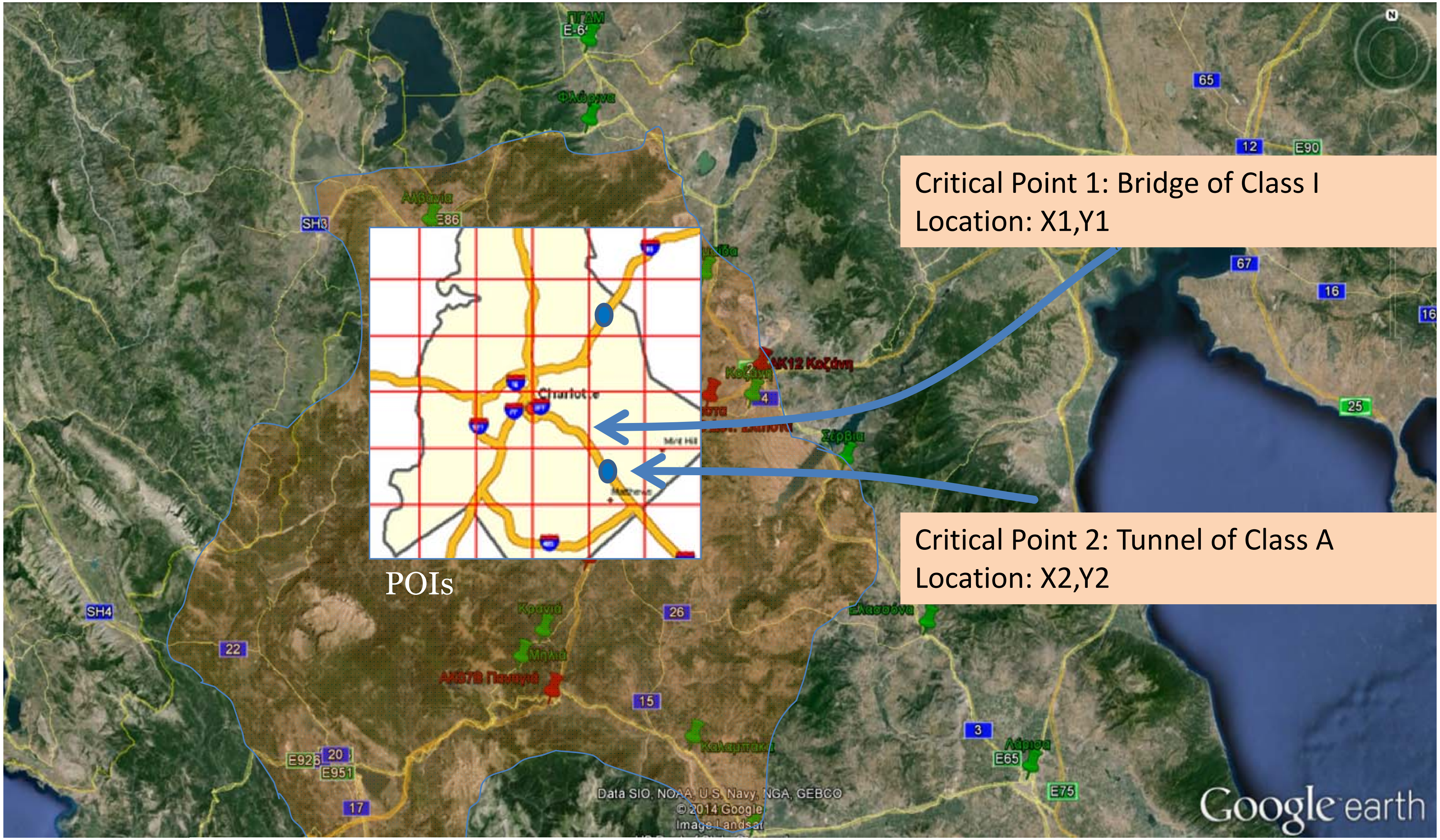


Distribution of over 30,000 earthquakes with magnitudes larger or equal to 3.5 for the period 1000 – 2007, documented by their damaging ef through history or recorded with modern instrumental seismic networks.

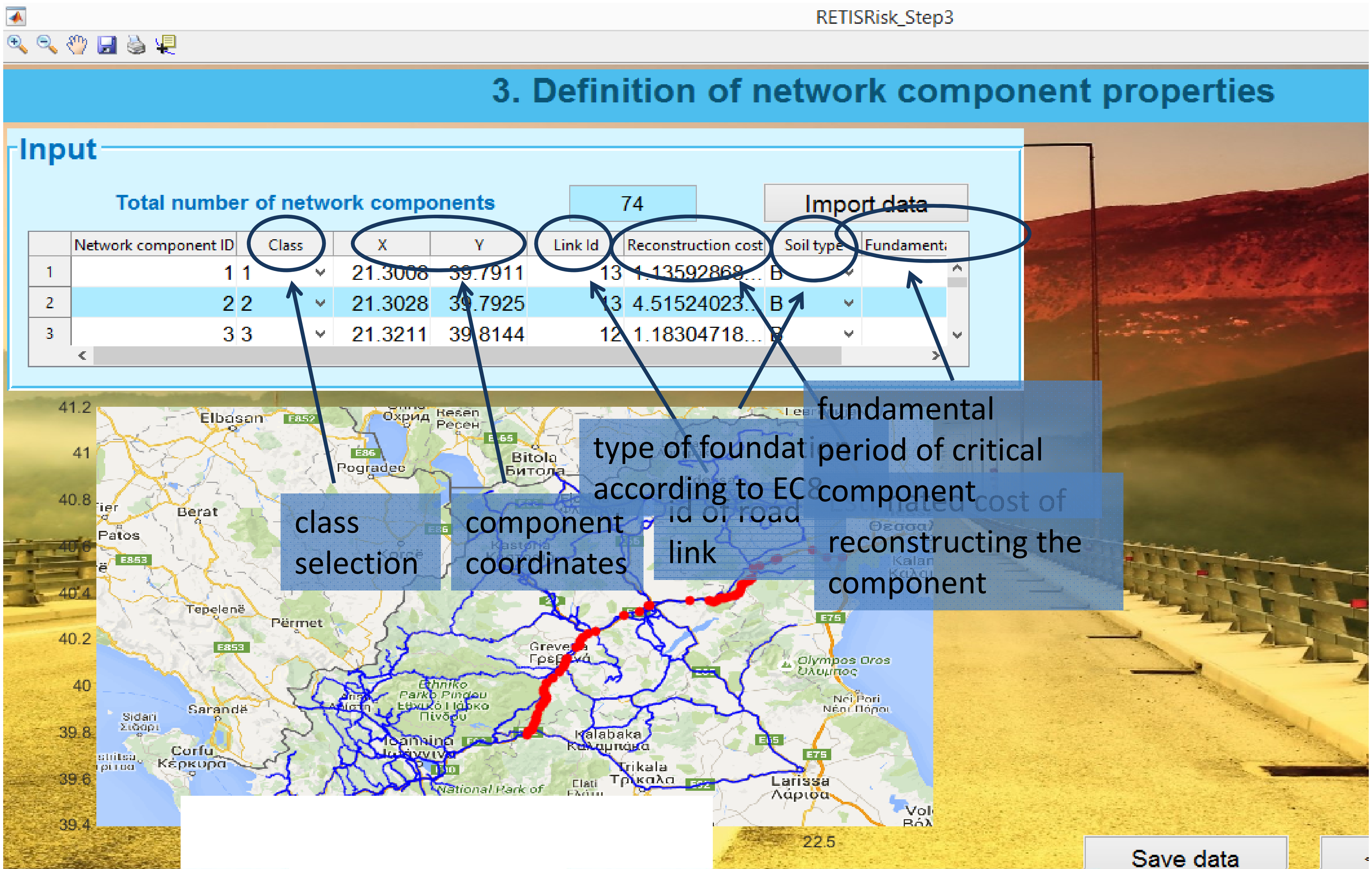
1. Area of study



2. Network Grid (portfolio of critical nodes)



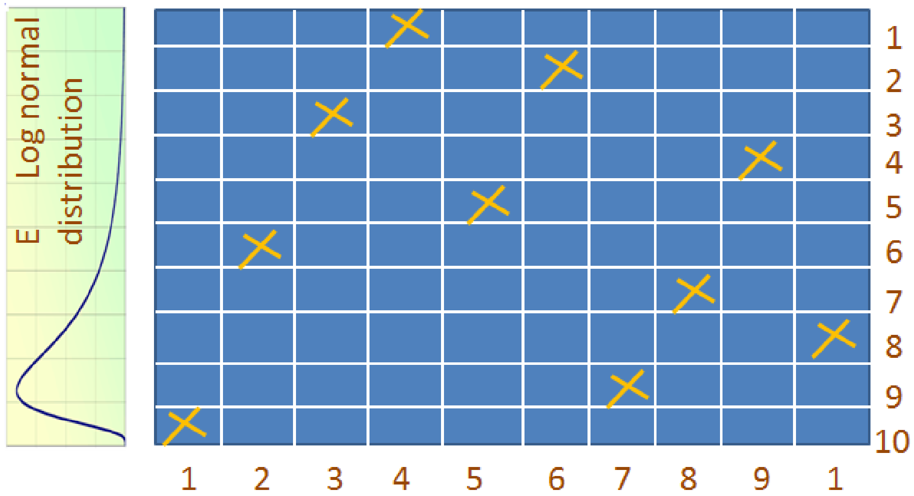
3. Classes of Critical Components



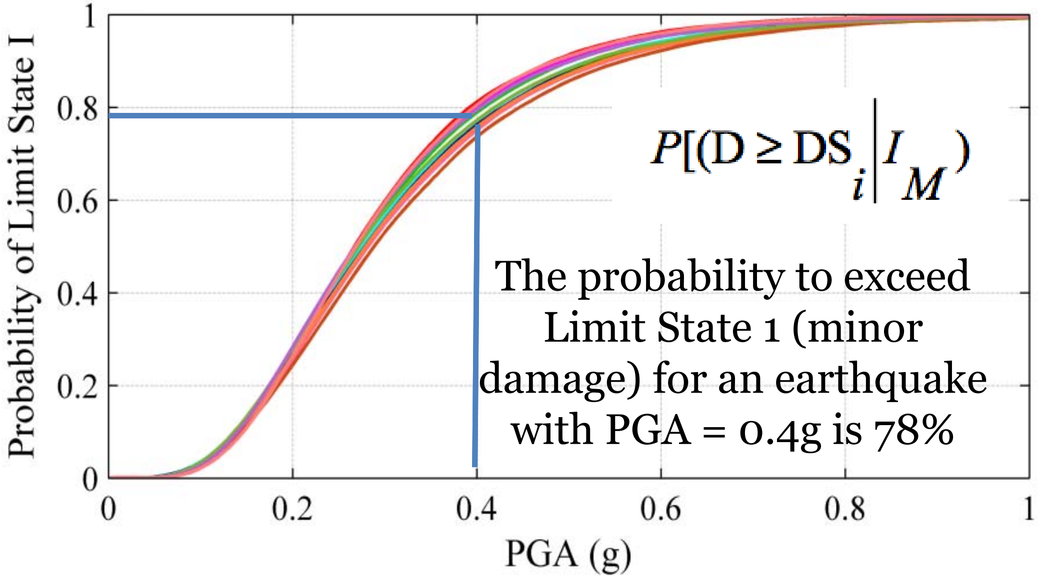
Seismic fragility of bridges within the highway network

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

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



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



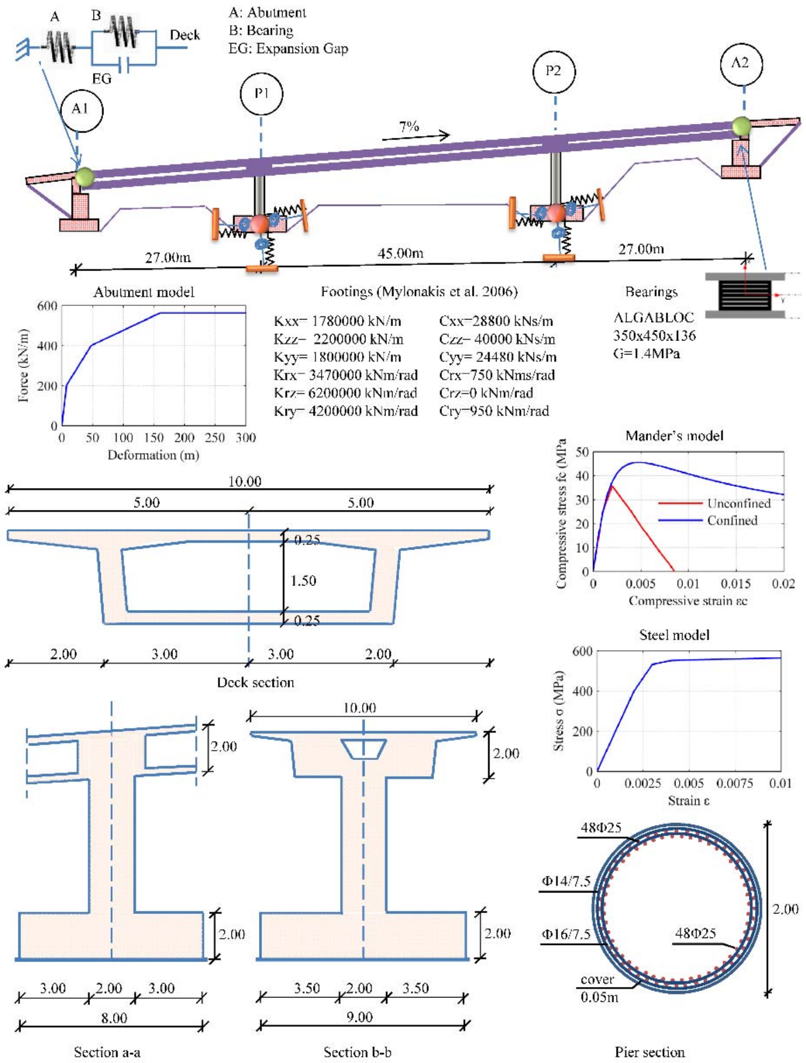
1. For each bridge class
2. Introduce uncertainty in material properties, geometry, finite element modelling, ground motion
3. Generate analysis sample (Monte Carlo, Latin Hybercube sampling)
4. Run series of nonlinear response history analyses
5. Define limit states
6. Compute structural damage proxies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

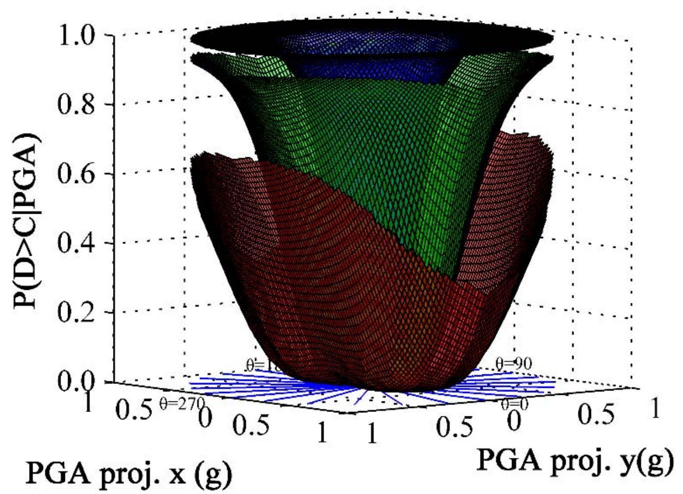
4. Vulnerability of each class of structures (1/2)

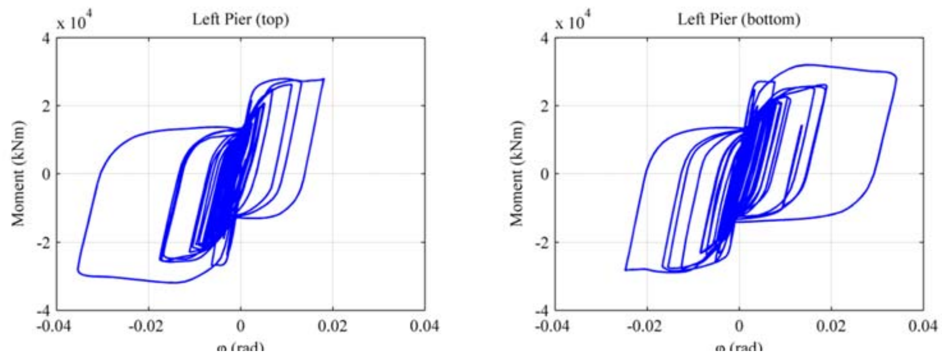
Multi-damage Fragility

Limit State	Piers / EDP : d (m) Local	Global	Abutments EDP: d (m)	Bearings EDP: γ (%)
LS 1 – Minor/Slight damage	φ_1:φ_y	d_1: $\min\begin{Bmatrix} d(\varphi_1) \\ d(V_1) \end{Bmatrix}$	$d_1 = 1.1 \cdot d_{gap}$ $(\mu_{\varphi,backwall} = 1.5)$	20
LS 2 – Moderate damage	φ_2: min (φ: $\varepsilon_c > 0.004$, φ: $\varepsilon_s \geq 0.015$)	d_2: $\min\begin{Bmatrix} d(\varphi_2) \\ d(V_2) \end{Bmatrix}$	$d_2 = 0.01 \cdot h_{backwall}$	100
LS 3 – Major/Extensive damage	φ_3: min (φ: $\varepsilon_c \leq 0.004 + 1.4 \cdot \rho_w \cdot \frac{f_{yw}}{f_{cc}}$ φ: $\varepsilon_s \geq 0.06$)	d_3: $\min\begin{Bmatrix} d(\varphi_3) \\ d(V_3) \end{Bmatrix}$	$d_3 = 0.035 \cdot h_{backwall}$	200
LS 4 – Failure/Collapse	φ_4: min (φ: $M < 0.90 \cdot M_{max}$, φ: $\varepsilon_s \geq 0.075$)	d_4: $\min\begin{Bmatrix} d(\varphi_4) \\ d(V_4) \end{Bmatrix}$	$d_4 = 0.1 \cdot h_{backwall}$	300

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



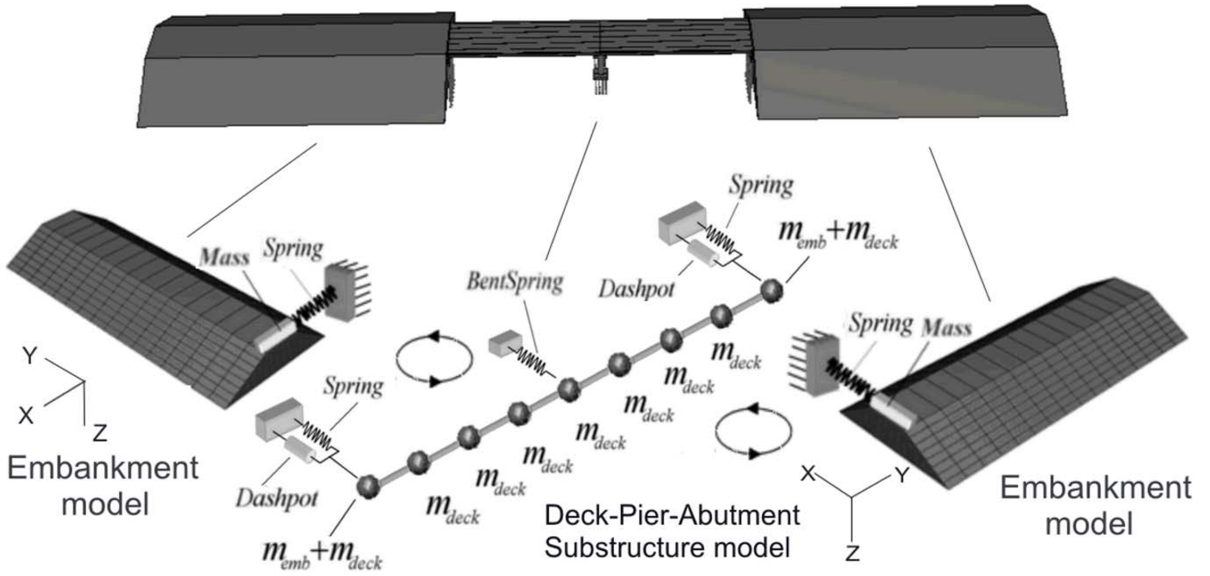


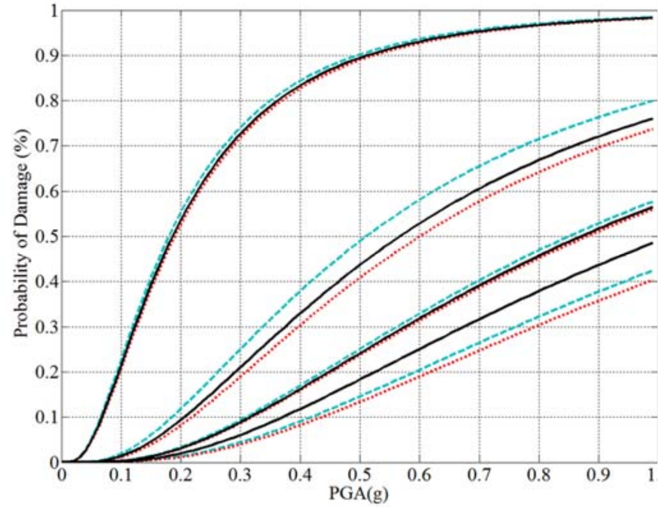


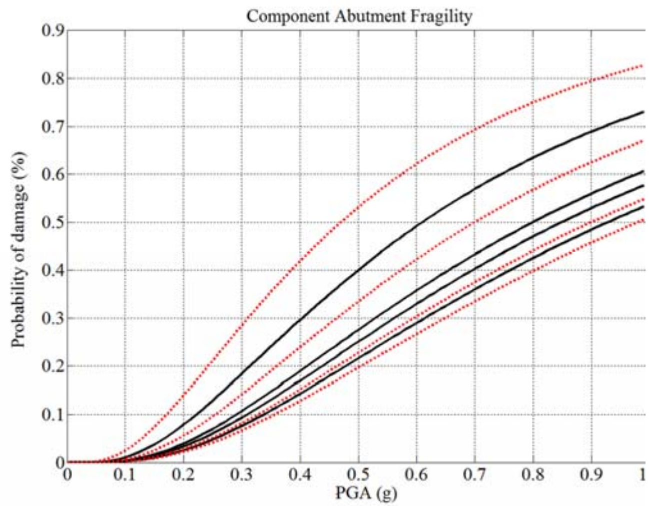
$$P_{sys}[D > C|IM] = \frac{\sum_{i=1}^{n} a_i Pi[C < D|\theta_i]}{\sum_{i=1}^{n} a_i}$$

Taskari & Sextos (2015)

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







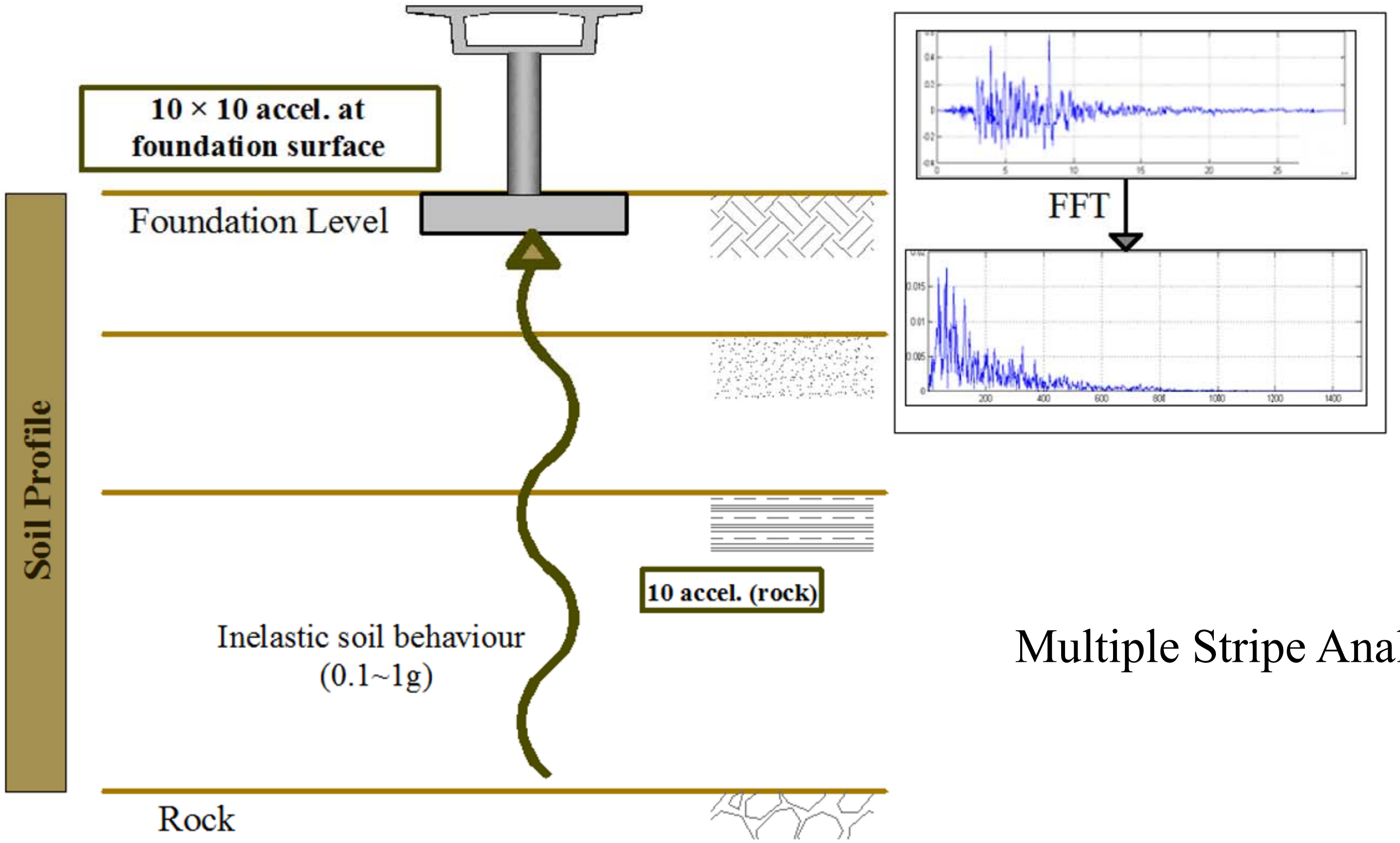
$$M^*_{emb} = B_c \cdot \int_0^{L_c}\int_0^{H} \rho \cdot \Phi^2(z,y) \cdot dz \cdot dy$$

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

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

Stefanidou, Sextos. Kappos, Kotsoglou (2016)

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



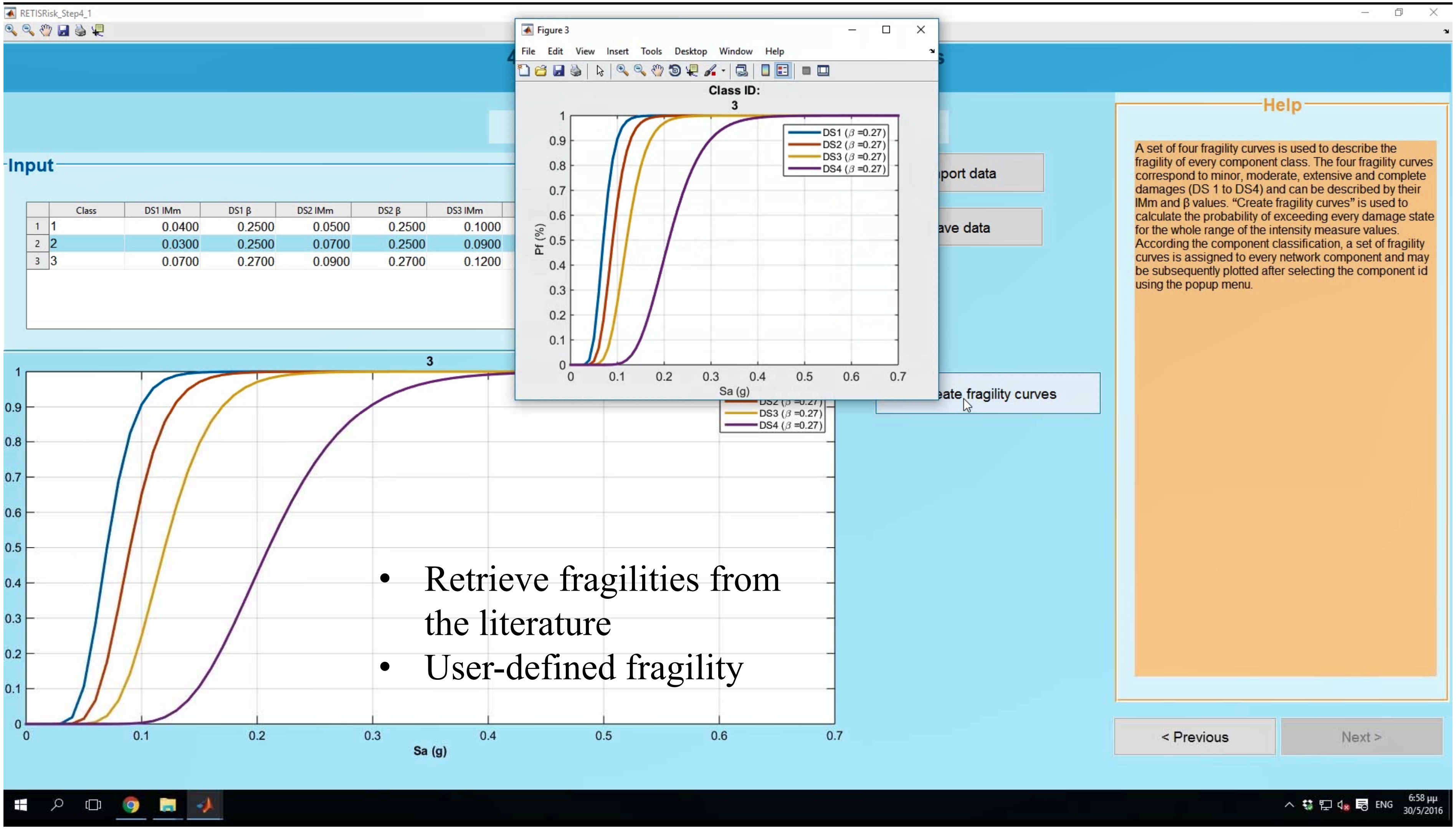
Multiple Stripe Analysis

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

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

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

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



- Retrieve fragilities from the literature
- User-defined fragility

5. Vulnerability of each class of tunnels

•Fragility of:

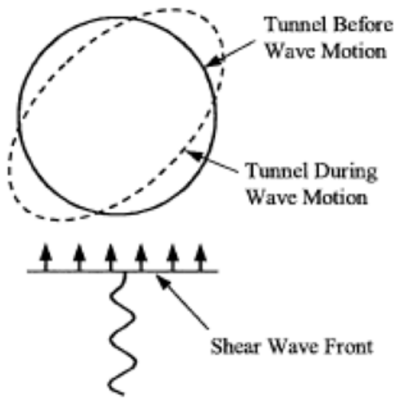
i. Tunnels

ii. Slopes

• PGA/PGV/PGD as Intensity Measure

• Definition of Limit States

5. Vulnerability of each class of tunnels



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

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

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

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

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

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

Limit States

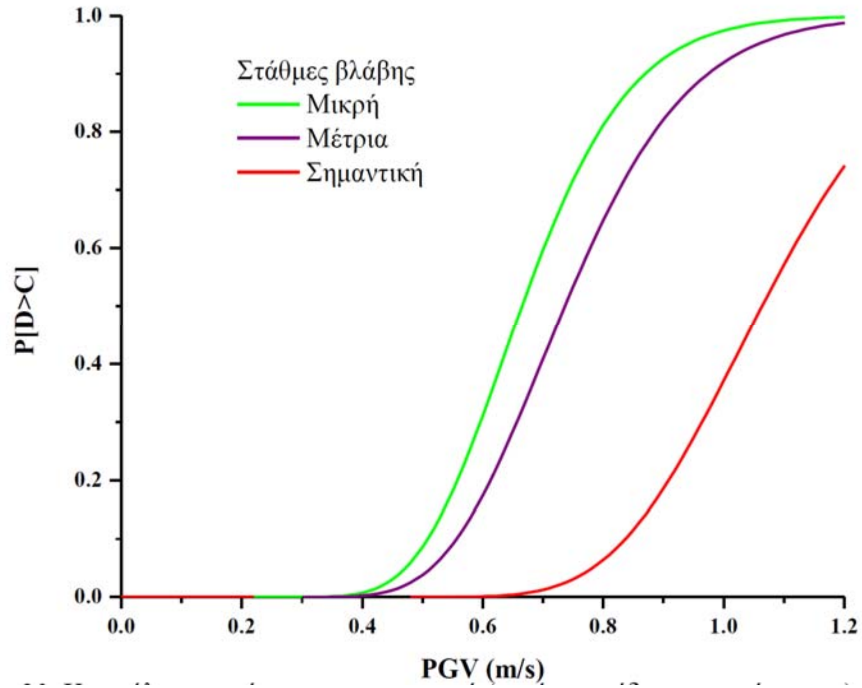
No damage
$\varepsilon_t/\varepsilon_{c1} < 1.0$

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

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

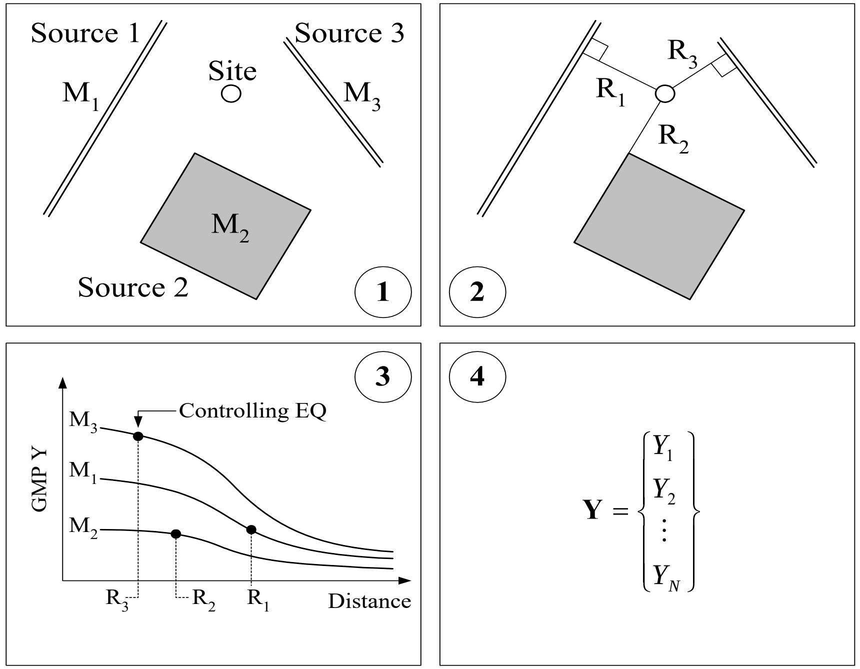
Collapse
$\varepsilon/\varepsilon_{c1} > 2.0$

Mylonakis, Maravas, Taskari, Sextos (2016)



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

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

$$\underbrace{\nu_i f_{M,R,E}(m,r,\varepsilon)_i}_{} = \underbrace{\nu_i f_M\left(m \middle| \mathbf{x}_{hyp}\right) f_{X_{hyp}}\left(\mathbf{x}_{hyp}\right)}_{} \underbrace{f_R\left(r \middle| m, \mathbf{x}_{hyp}, \boldsymbol{\theta}_i\right)}_{} \underbrace{f_E(\varepsilon)}_{}$$

how many times per year do all possible levels of ground motion occur from source i?

how many times per year does an earthquake of $M=m$ occur in source i with a hypocentre at $\mathbf{x}_{hyp}$?

when this event occurs, what sort of rupture does it produce?

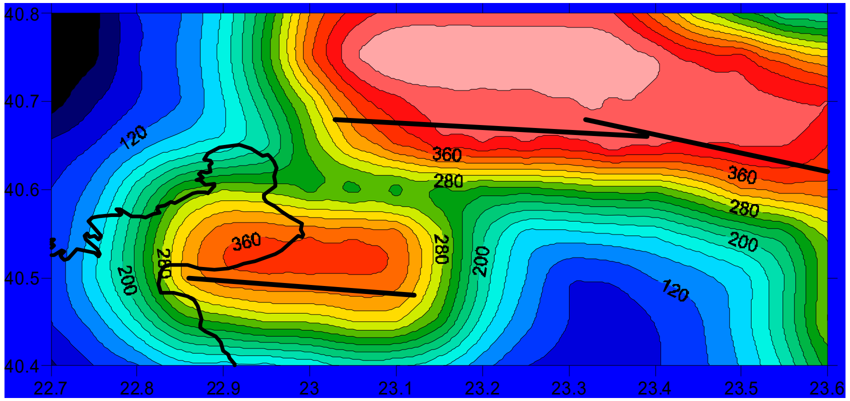
how likely are the possible GM values for this scenario?

6. Seismic Hazard Assessment

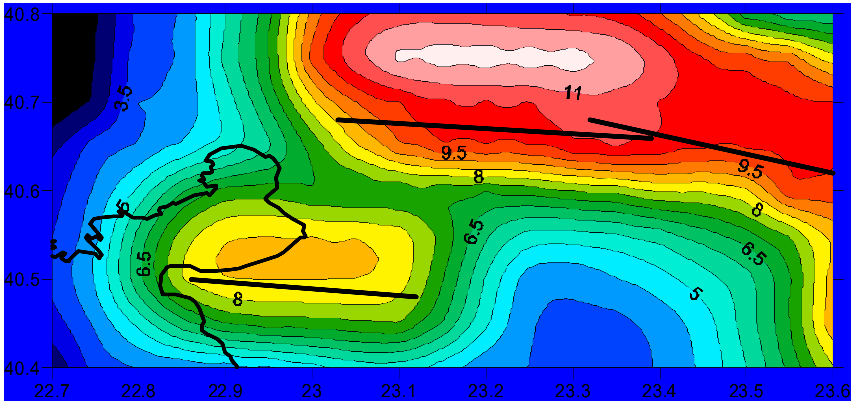
Geographical distribution of expected Intensity Measures

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

PGA (cm/sec²)



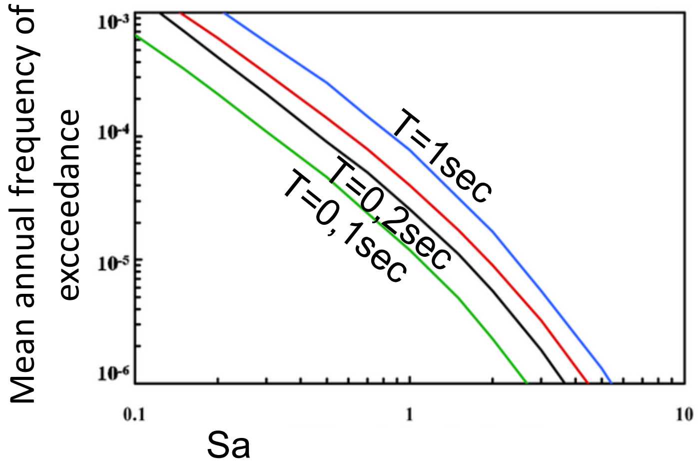
PGV (cm/sec)



Area Grid

1x1km grid

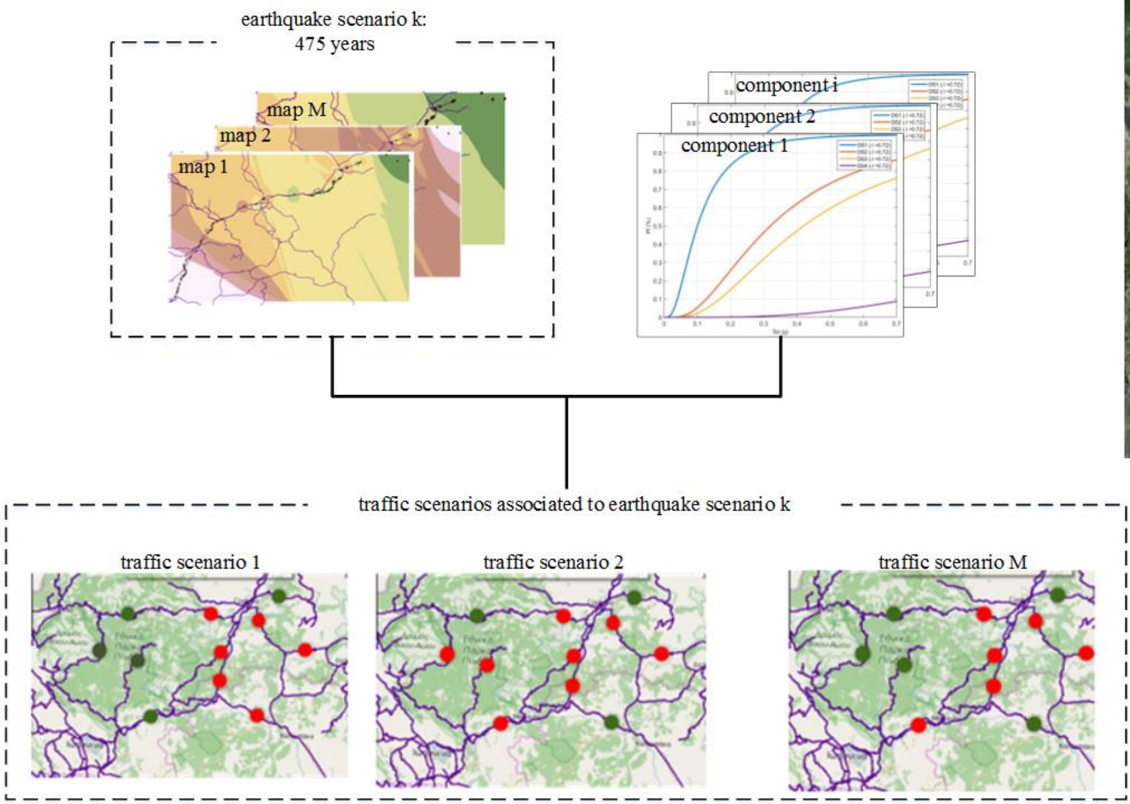
Hazard curves

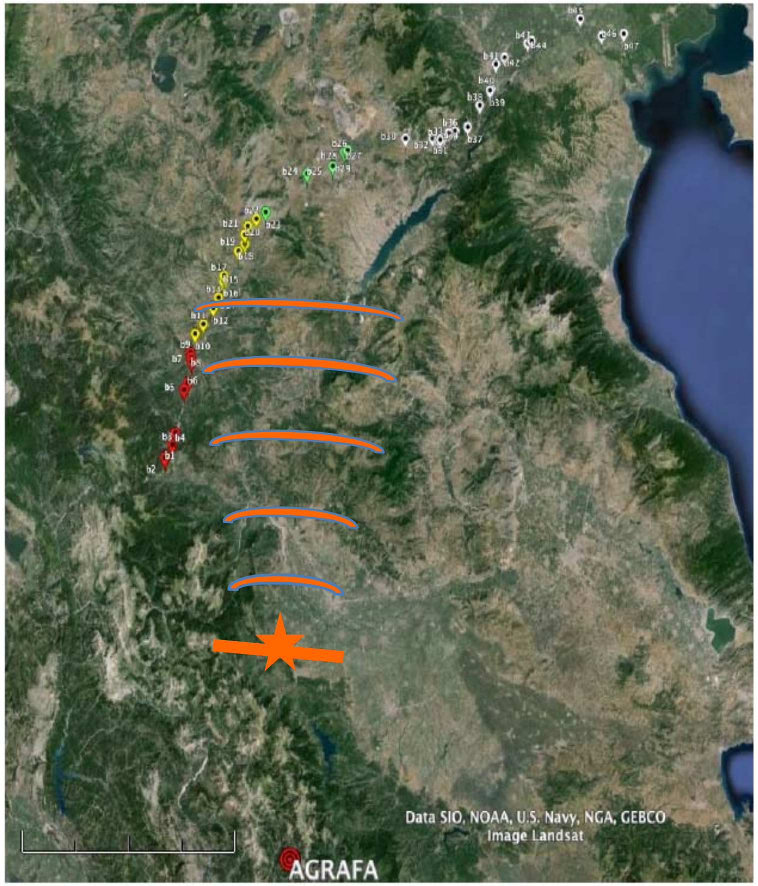


6. Seismic Hazard Assessment

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

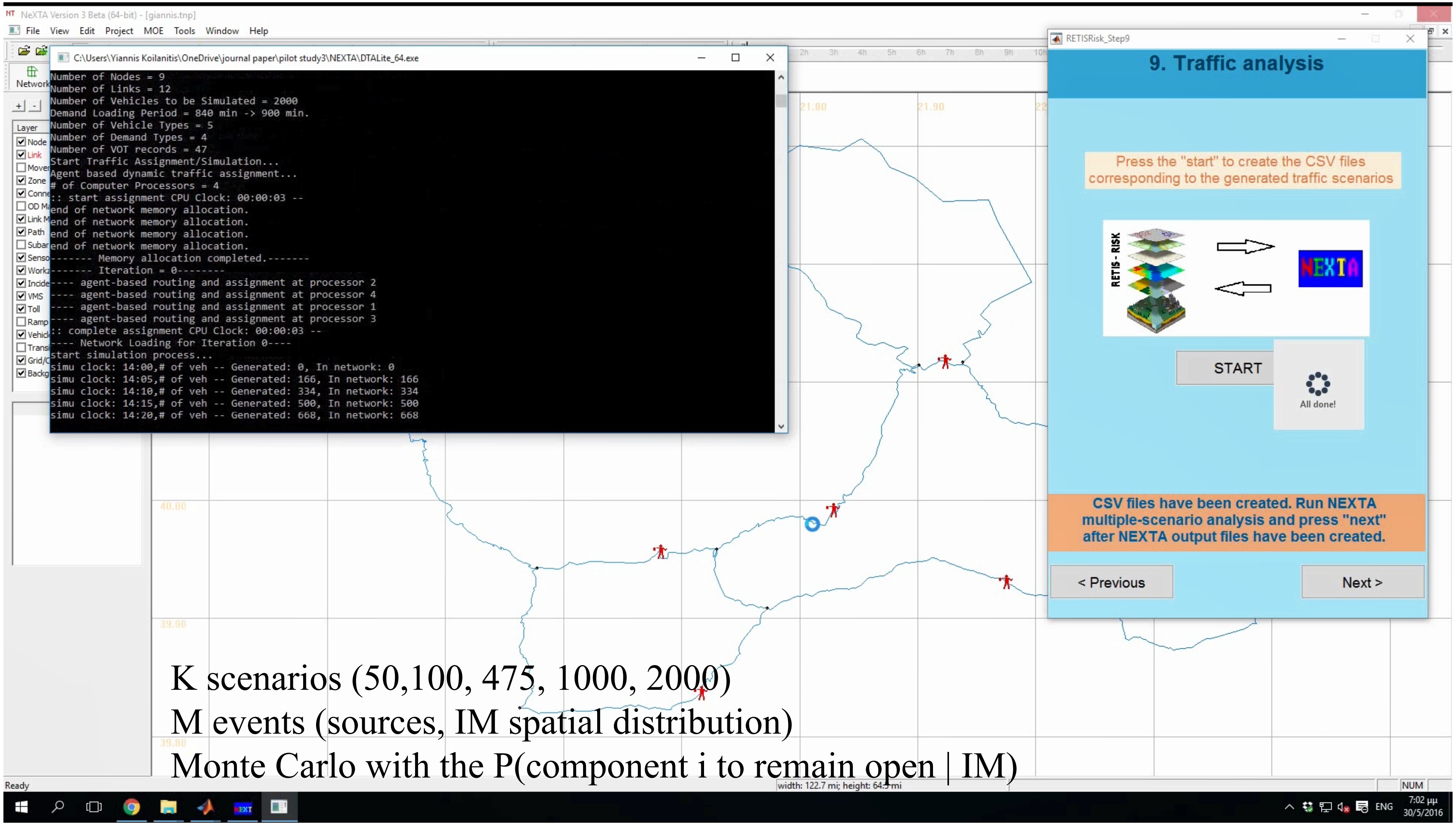
$$\tilde{T}_r = \begin{cases} 1 \;\; if \;\; P_{i,k,m}[D \geq DS_2] \,|\, im_{i,k,m} < 0.5 \\ 0 \;\; if \;\; P_{i,k,m}[D \geq DS_2] \,|\, im_{i,k,m} \geq 0.5 \end{cases}$$





Traffic flow redistribution given the network components functionality

7. Traffic analysis



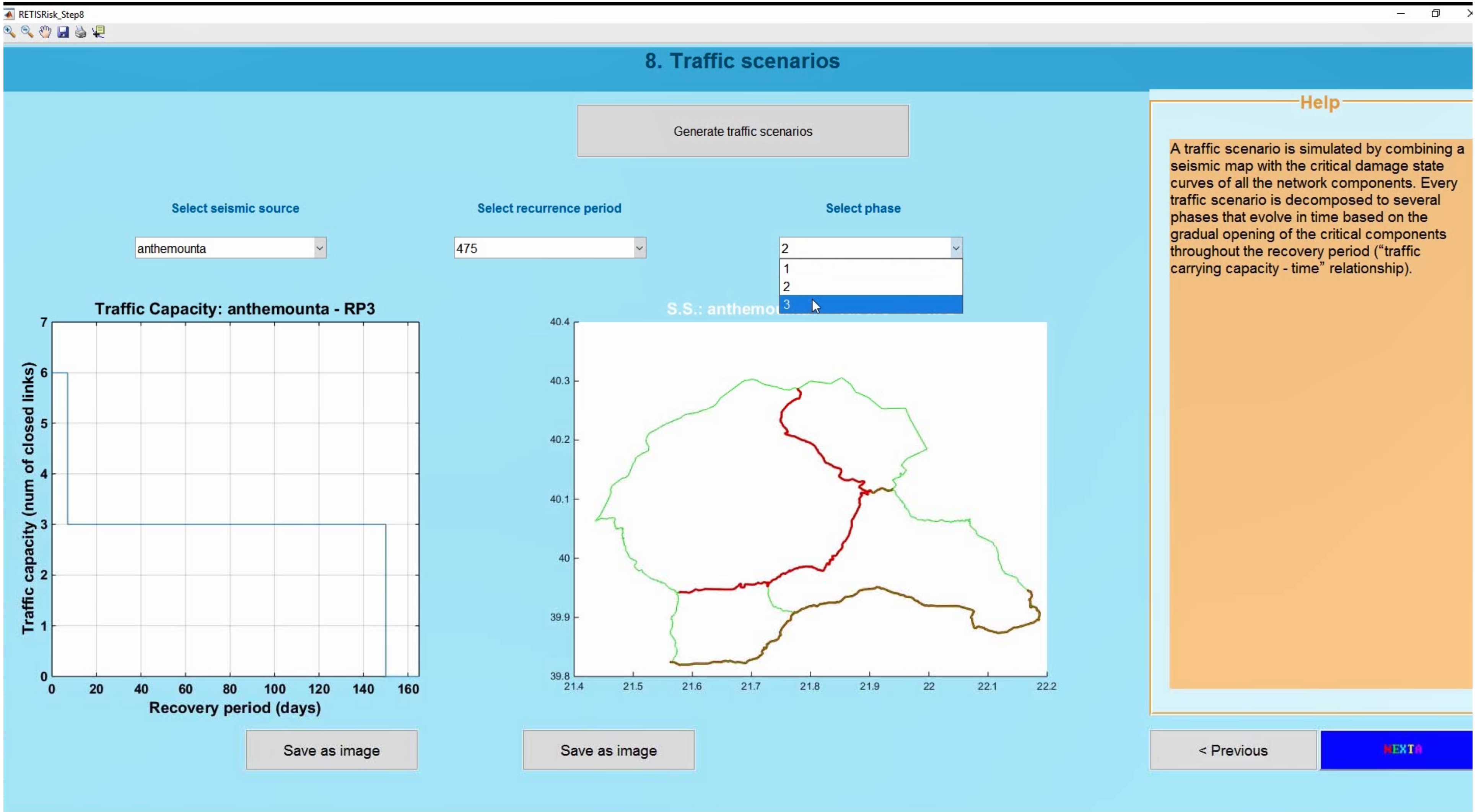
K scenarios (50,100, 475, 1000, 2000)

M events (sources, IM spatial distribution)

Monte Carlo with the P(component i to remain open | IM)

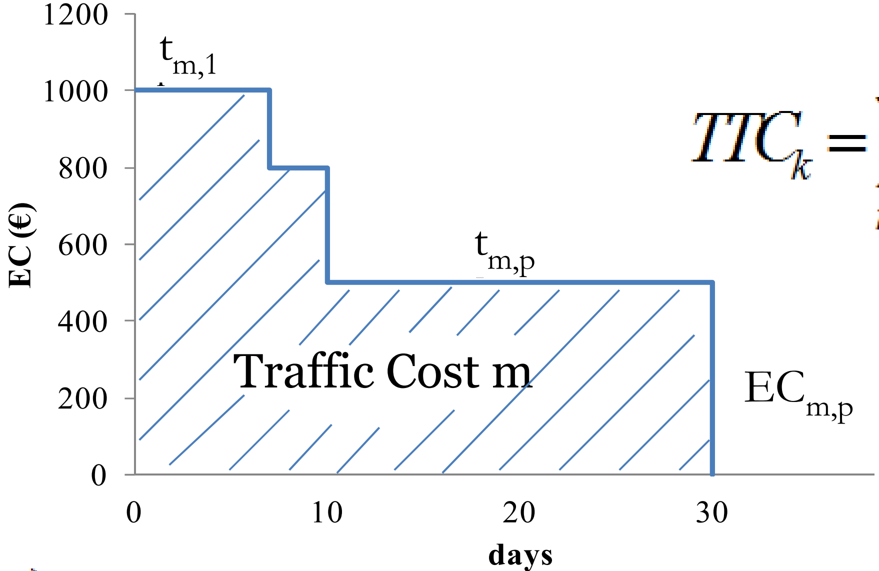
7. Repair cost and restoration vs. time

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*



Additional daily cost

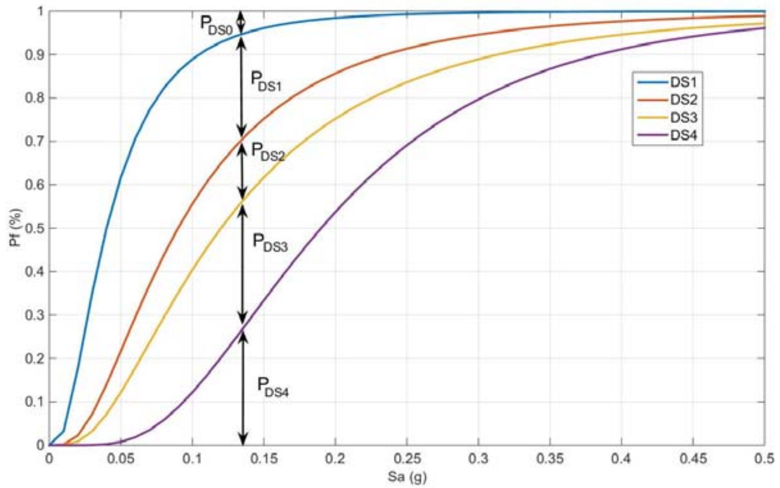
$$TTC_k = \sum_{m=1}^{M} \sum_{p=1}^{P} EC_{m,p} \cdot t_{m,p}$$

$$EC_p = D_p \cdot VOT$$

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

ECp	: additional cost due to traffic conjunction during phase p (per time unit)
VOT	: value of time
Dp	: total delays during phase p
Vjp	: traffic load in network link j
tjp	: travel time in network link j
Vjo	: traffic load in network link j before earthquake occurrence
tjo	: 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

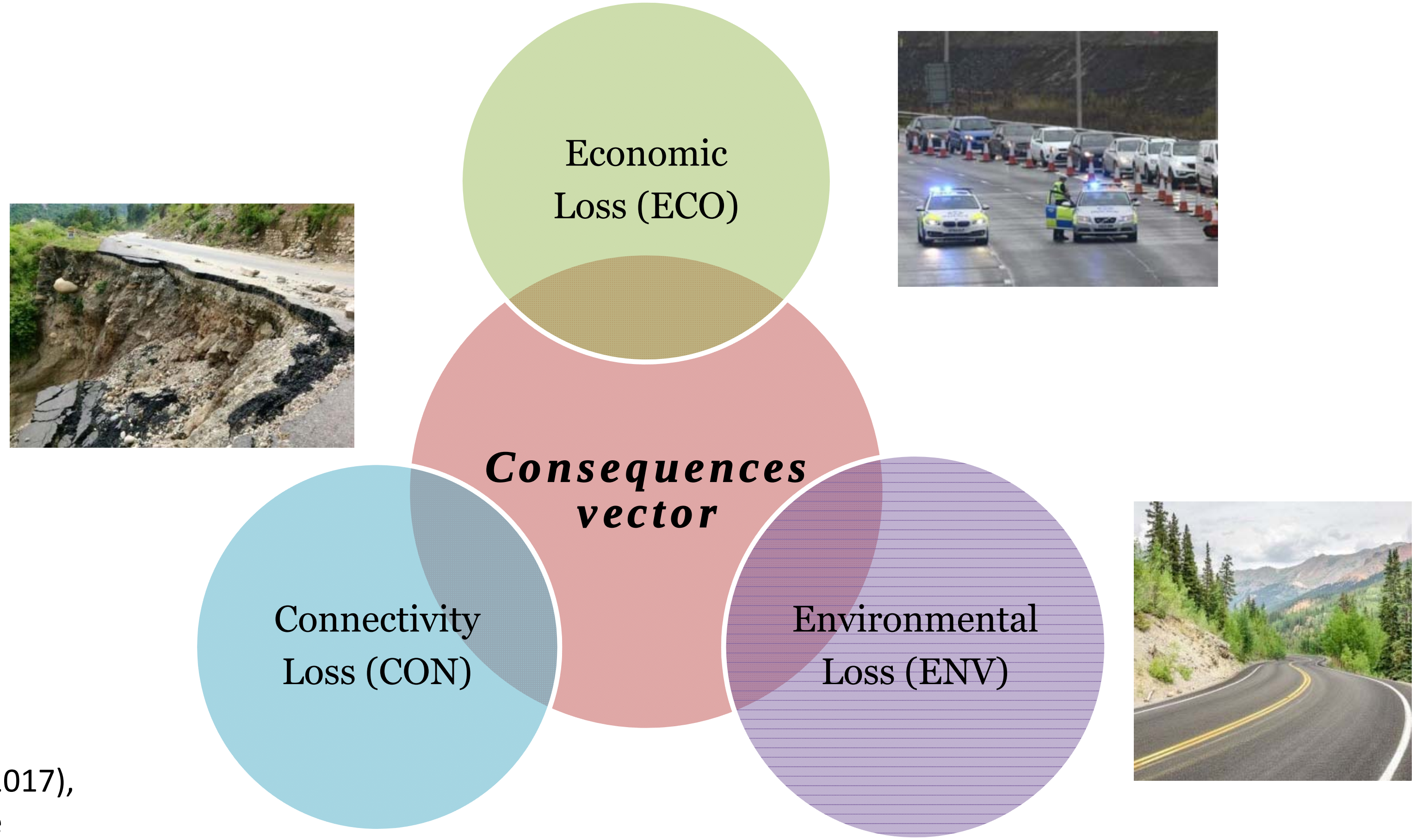
Total (for the entire network) Structural Cost :

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

N: total number of critical network components

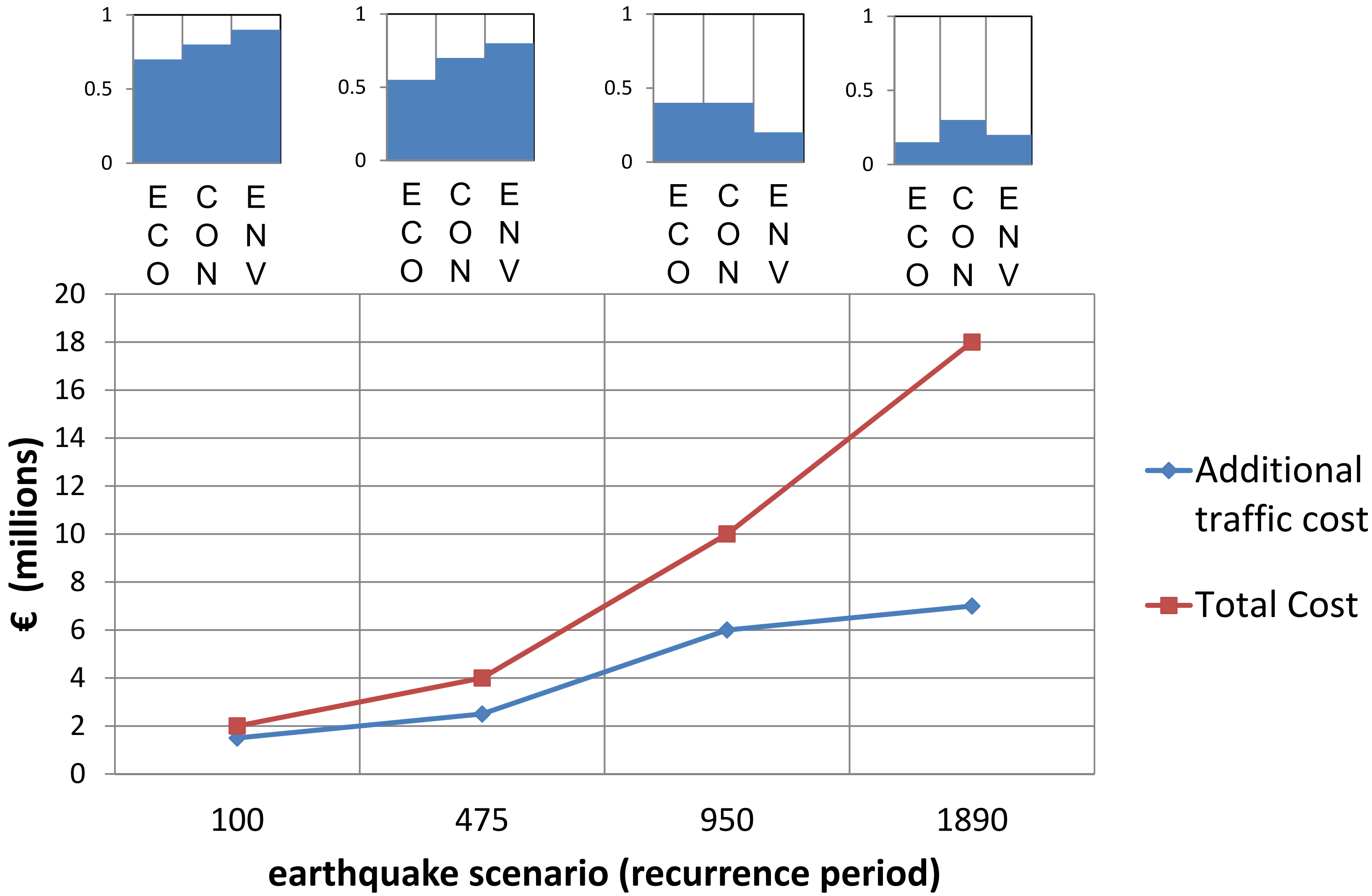
9. Consequence analysis

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

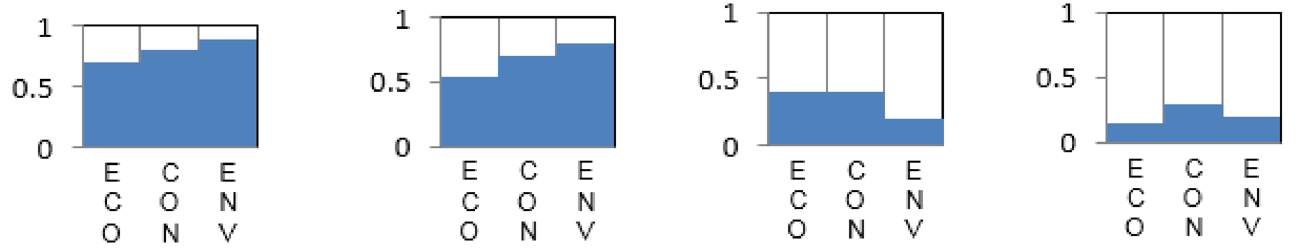


Sextos et al. (2017), 16WCEE, Chile

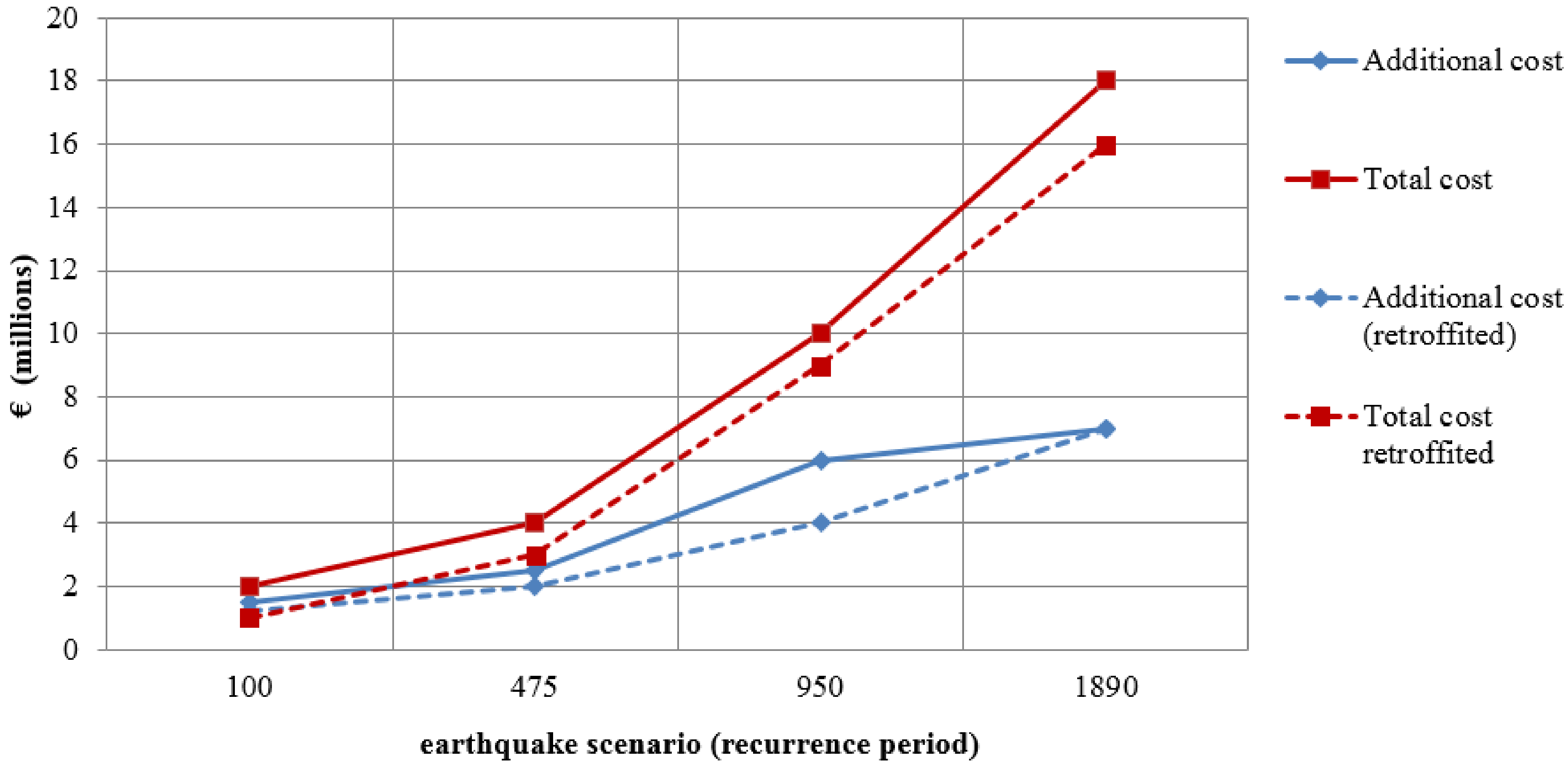
10. Decision making



10. Decision making



To retrofit or not?



SHM and (nearly) Real-time Seismic Risk Assessment

Post-quake

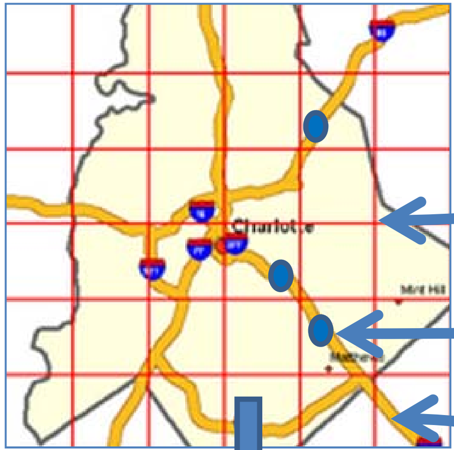
Minimize implications on disaster response (immediate after) and recovery (in the long term)

Update with actual IM

Data

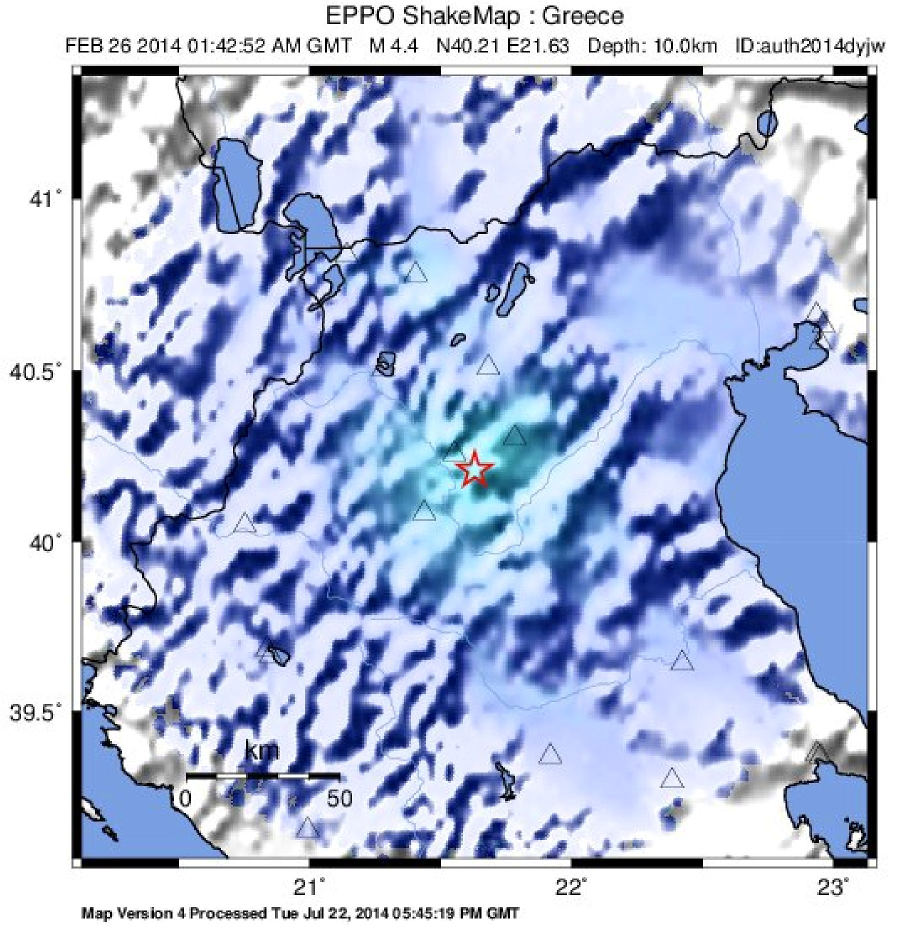
Processing

Area Grid



Calculation of **qualitative** and **quantitative** indicators

(AFTER the earthquake based on structural monitoring & Shake Maps)



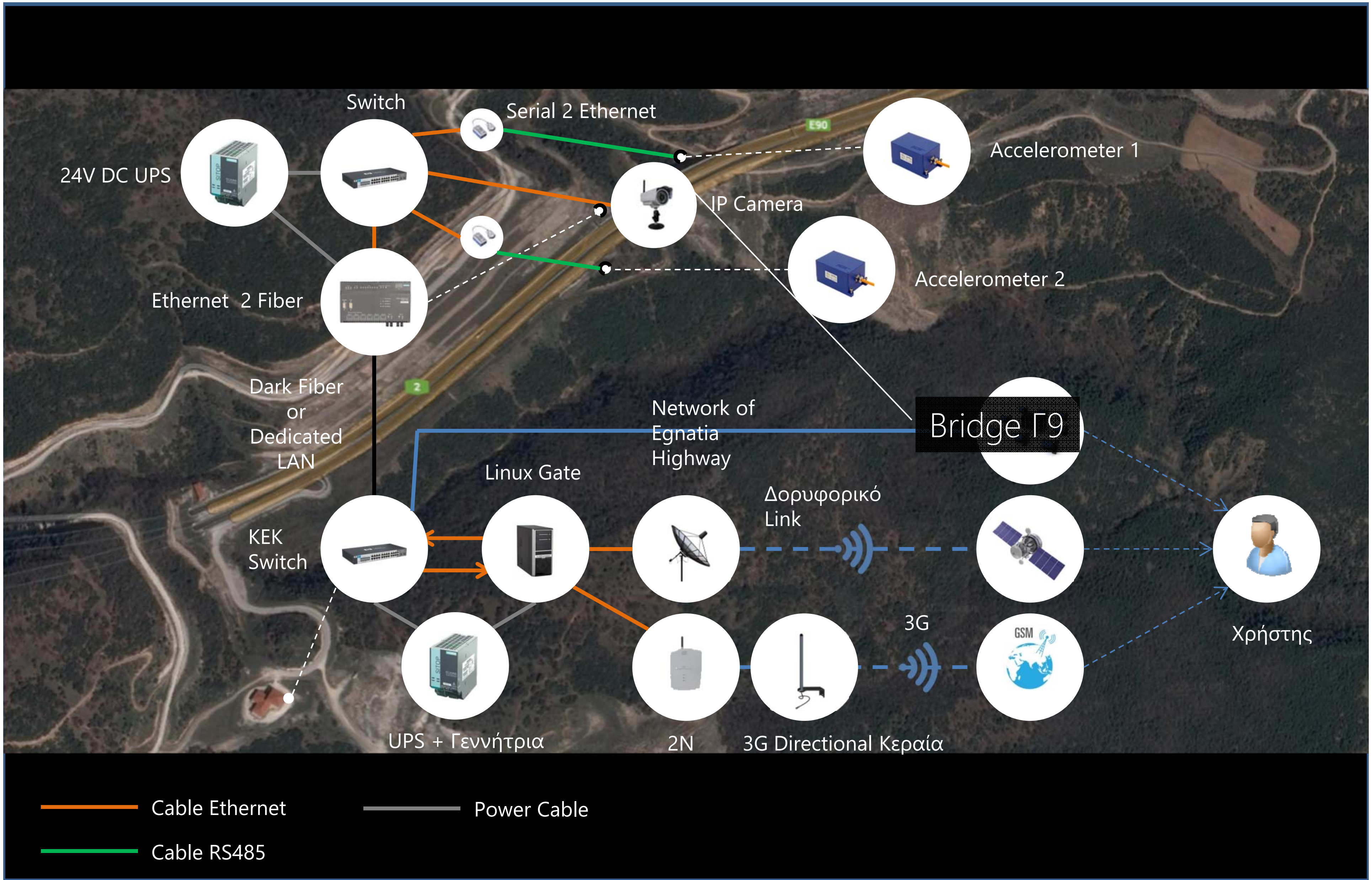
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I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

Update with actual Sa(T): Satellite link



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

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Ευρωπαϊκή Ένωση
Ευρωπαϊκό Κοινωνικό Ταμείο
ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΠΡΟΓΡΑΜΜΑ
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ΕΣΠΑ 2007-2013
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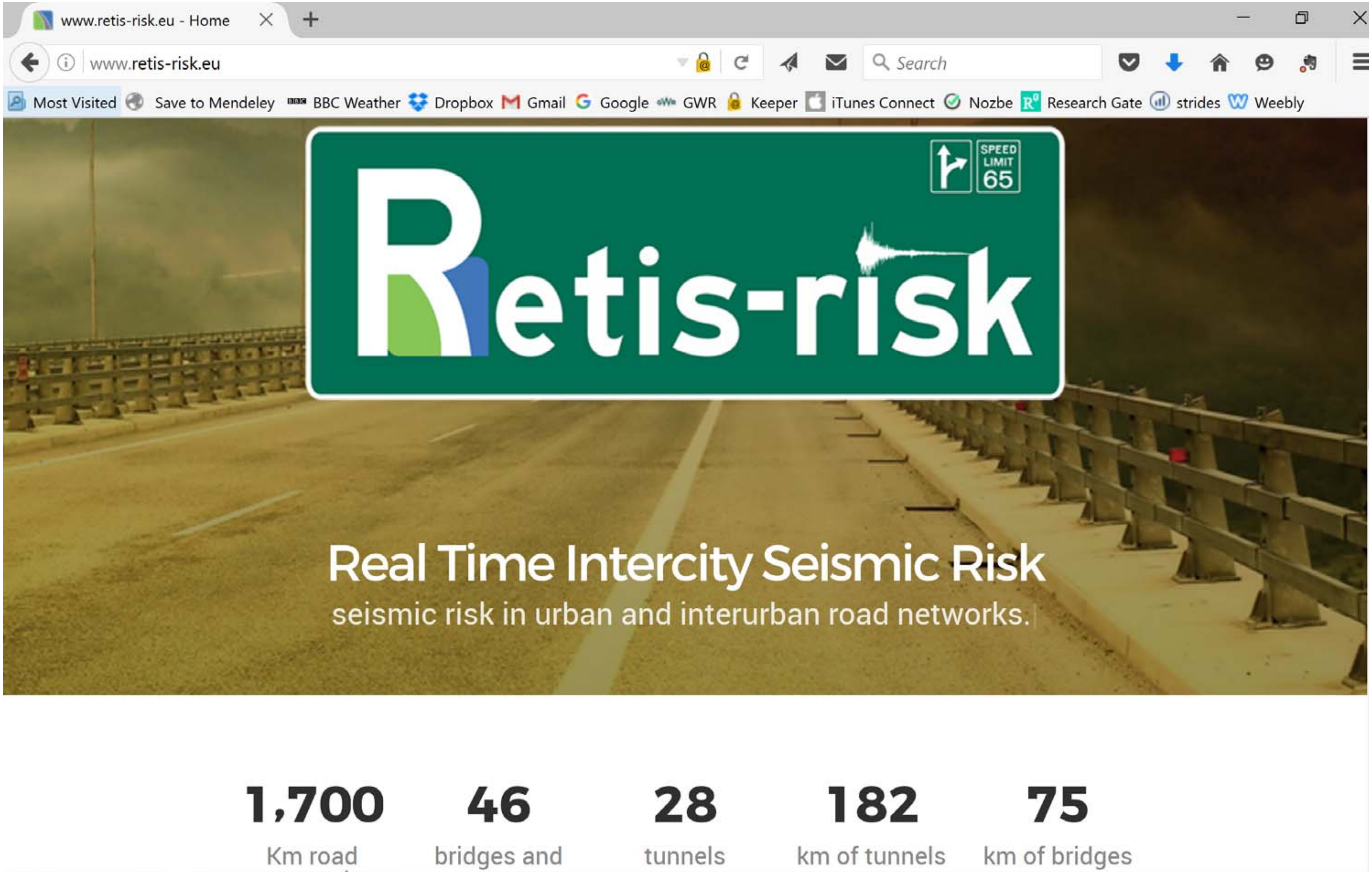
Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης



www.retis-risk.eu