Methodology, software and policy for optimum seismic resilience of highway networks

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Current state-of-practice

Probabilistic Framework

$$\lambda(DV) = \int \int \int G(DV|DM) \cdot dG(DM|EDP) \cdot dG(EDP|IM) \cdot d\lambda(IM)$$

Stakeholder

- Single component
- Single hazard

- Seismic Risk / Loss
- Loss Analysis
- Damage Analysis
- Response Analysis
- PSHA

- Quick Visual Inspection
- 2nd degree of assessment
- Repair / Strengthening

- Hazard Assessment
- Fragility Assessment
- Risk Assessment

Cornell & Krawinkler (2000)
Krawinkler & Miranda (2004)
FEMA (1997)
Moehle (2004)
multiple roadway network components
Japan Tohoku 2011 earthquake

Direct loss
- of life due to collapse or structural failure
- of property and utility service (e.g., the collapse of a bridge carrying utilities).

Indirect Loss
- of life due to inability to respond to secondary catastrophes (fires) and provide emergency medical aid
- delayed recovery operations
- release of hazardous products (e.g., losses from tank cars derailed by track failure, gas leaks from ruptured utility lines) and environmental impacts
- losses due to interruption of access (e.g., export losses due to port damage)
- disruption of economic activity across the community directly affected and the nation

319 $billion

direct vs. indirect loss

619 $billion
Speed of recovery

March 23rd, 2011

Japan fixed this quake-damaged road in just six days.
Indirect loss accumulates with time
Loss of functionality is not proportional to the extent of damage
Network analysis

Assess

Functionality and not only Structural Integrity

Focus

on the Network and not on a single Structure
Resilience at the Network Level

= 

the ability to rebound quickly from loss of functionality of the entire infrastructure network in the affected area
Resilience at the Network Level

Pre-disaster & Post-disaster

Mitigate Risk (in terms of direct damage and loss) & Minimize implications on disaster response (immediate after) and recovery (in the long term)
Resilience-based management of networks

\[ R = \int_{t_{\text{OE}}}^{t_{\text{OE}}+T_L} \frac{Q(t)}{T_L} dt \]

\[ Q(t) = [1 - L(t, T_{\text{RE}})] [H(t - t_{\text{OE}}) - H(t - (t_{\text{OE}} + T_{\text{RE}}))] \times \int_{t_{\text{OE}}}^{t_{\text{OE}}+T_L} [1 - L(t, T_{\text{RE}})] \]
Resilience-based management of highway networks

for

State & Stakeholders

by integrating

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

- nodes (id, coordinates)
- links (id, start/end node, length)
- OD matrix
- traffic zones
- link traffic capacity & speed limits
- Pre-earthquake traffic data
- activity zones
- POIs & links/activity zone environmentally sensitive links
- Network operation data

Methodology

Seismic hazard analysis

- Seismic maps
- Seismic hazard levels
- Segments of seismic sources

Fragility analysis

- Fragility Classes
- Probabilistic damage distributions
- Fragility curves

Recovery analysis

- Monte Carlo
  - Damage samples
  - Restoration matrix
  - Recovery phases

Network topology
Case study

InterCity Network for the Prefecture of Western Macedonia, Greece
Sextos & Kilanitis: Methodology, software and policy for optimum seismic resilience of highway networks
- Construction along the ancient Roman path of Egnatia
- 680 km highway
- 42 km of bridges (490 bridges and overpasses)
  - Maximum bridge length: 1100 m
  - Maximum pier height: 90 m
a natural laboratory for earthquake engineering research

- Construction along the ancient Roman path of Egnatia
- 680km highway
- 42km of bridges (490 bridges and overpasses)
- Maximum bridge length: 1100m
- Maximum pier height: 90m
Bridge G4 and Polymylos-Veria Bridge, Greece
Egnatia Highway

Metsovitikos Bridge, Greece
Egnatia Highway

Metsovitikos Bridge, Greece
Egnatia Highway

Length: 850m (left branch), 640 (right branch)
Deck: continuous, box-shaped, prestressed concrete
Curvature: 450m radius (the larger curved bridge in Greece)
Number of spans: 10
Maximum pier height: 30m
Construction method: Incremental launching
Foundation: piles

Sextos & Kilanitis: Methodology, software and policy for optimum seismic resilience of highway networks
Software architecture

Data processing

Data collection

Internet

Literature

Transportation agency

GIS

Shapefile

GIS Data

Shapefile

Matlab code

Dynamic traffic assignment engine "DTALite"

Matlab GUI

Diagrams

Traffic maps

Image files

Input data

Output data

Spreadsheets

Matlab GUI

Shapefiles

Google maps

Spreadsheet

Matlab GUI

Shapefile

Google maps

Image files
1. Area of study

Area: 9,451 km²
Population: 283,689
2. Network Grid (portfolio of critical nodes)

Critical Point 1: Bridge of Class I
Location: X1,Y1

Critical Point 2: Tunnel of Class A
Location: X2,Y2
2. Network Grid (portfolio of critical nodes)
3. Classes of critical components
4a. Seismic fragility of bridges & overpasses

The probability to exceed Limit State 1 (minor damage) for an earthquake with PGA = 0.4g is 78%

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

The probability to exceed Limit State 1 (minor damage) for an earthquake with PGA = 0.4g is 78%
## 4a. Seismic fragility of bridges & overpasses

### Multi-damage fragility

<table>
<thead>
<tr>
<th>Limit State</th>
<th>Piers / EDP: $d$ (m)</th>
<th>Abutments EDP: $d$ (m)</th>
<th>Bearings EDP: $\gamma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LS 1 – Minor/Slight damage</strong></td>
<td>$\varphi_i \leq \varphi_f$</td>
<td>$\min \left{ \frac{d(\varphi_1)}{d(V_1)} \right}$</td>
<td>$d_1 = 1.1 \cdot d_{gap}$ (</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\mu_{\varphi,backwall} = 1.5$</td>
</tr>
<tr>
<td><strong>LS 2 – Moderate damage</strong></td>
<td>$\varphi_2$: min ($\varphi$: $\varepsilon_c &gt; 0.004$, $\varphi$: $\varepsilon_s \geq 0.015$)</td>
<td>$\min \left{ \frac{d(\varphi_2)}{d(V_2)} \right}$</td>
<td>$d_2 = 0.01 \cdot h_{backwall}$</td>
</tr>
<tr>
<td><strong>LS 3 – Major/Extensive damage</strong></td>
<td>$\varphi_3$: min ($\varphi$: $\varepsilon_c \leq 0.004 +$ 1.4 $\cdot \rho_w \cdot \frac{f_{yw}}{f_{ce}}$, $\varepsilon_s \geq 0.06$)</td>
<td>$\min \left{ \frac{d(\varphi_3)}{d(V_3)} \right}$</td>
<td>$d_3 = 0.035 \cdot h_{backwall}$</td>
</tr>
<tr>
<td><strong>LS 4 – Failure/Collapse</strong></td>
<td>$\varphi_4$: min ($\varphi$: $M &lt; 0.90 \cdot M_{\text{max}}$, $\varphi$: $\varepsilon_s \geq 0.075$)</td>
<td>$\min \left{ \frac{d(\varphi_4)}{d(V_4)} \right}$</td>
<td>$d_4 = 0.1 \cdot h_{backwall}$</td>
</tr>
</tbody>
</table>

Taskari & Sextos (2015) EESD
4a. Seismic fragility of bridges & overpasses

Varying angle of incidence

<table>
<thead>
<tr>
<th>In (γ)</th>
<th>Left abutment</th>
<th>PSDM</th>
<th>$R^2$</th>
<th>$\beta_{DM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta=0^\circ$</td>
<td>ln (0.010) + 0.76ln (PGA)</td>
<td>0.52</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>$\theta=15^\circ$</td>
<td>ln (0.009) + 0.70ln (PGA)</td>
<td>0.49</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>$\theta=30^\circ$</td>
<td>ln (0.011) + 0.73ln (PGA)</td>
<td>0.53</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>$\theta=45^\circ$</td>
<td>ln (0.010) + 0.67ln (PGA)</td>
<td>0.47</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>$\theta=60^\circ$</td>
<td>ln (0.010) + 0.66ln (PGA)</td>
<td>0.47</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>$\theta=75^\circ$</td>
<td>ln (0.011) + 0.70ln (PGA)</td>
<td>0.50</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>$\theta=90^\circ$</td>
<td>ln (0.01)</td>
<td>0.48</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>$\theta=105^\circ$</td>
<td>ln (0.01)</td>
<td>0.48</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>$\theta=120^\circ$</td>
<td>ln (0.01)</td>
<td>0.48</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>$\theta=135^\circ$</td>
<td>ln (0.01)</td>
<td>0.48</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>$\theta=150^\circ$</td>
<td>ln (0.00)</td>
<td>0.48</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>$\theta=165^\circ$</td>
<td>ln (0.00)</td>
<td>0.48</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>$\theta=180^\circ$</td>
<td>ln (0.01)</td>
<td>0.48</td>
<td>0.48</td>
<td></td>
</tr>
</tbody>
</table>

Taskari & Sextos (2015) EESD
4a. Seismic fragility of bridges & overpasses

Abutment-embankment & pier-foundation-soil interaction

\[ M_{emb}^* = B_c \cdot \int_{0}^{H} \rho \cdot \Phi^2(z, y) \cdot dz \cdot dy \]

\[ K_{emb}^* = G \cdot B_c \cdot \left( \int_{0}^{H} \Phi(z, y) \cdot \frac{d^2 \Phi(z, y)}{dz^2} \cdot dz \cdot dy + \int_{0}^{H} \Phi(z, y) \cdot \frac{d^3 \Phi(z, y)}{dy^2} \cdot dz \cdot dy \right) \]

4b. Seismic fragility of tunnels

- Fragility of:
  1. Tunnels
  2. Slopes
- PGA/PGV/PGD as Intensity Measure
- Definition of Limit States
4b. Seismic fragility of tunnels

Limit States

- **No damage**
  \[ \varepsilon_t / \varepsilon_c < 1.0 \]
- **Minor Damage**
  \[ 1.0 < \varepsilon_t / \varepsilon_c < 1.30 \]
- **Major Damage**
  \[ 1.30 < \varepsilon_t / \varepsilon_c < 2.0 \]
- **Collapse**
  \[ \varepsilon_t / \varepsilon_c > 2.0 \]

\[ \Delta R = \frac{1}{3} \left( \frac{1}{K F \gamma_{\max} d} \right) \]

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

\[ F = \frac{2G_s (1-v_s^2) R^3}{6\varepsilon_c I_c} \]

\[ \gamma_{\max} = \frac{PGV}{1.7V_s} \]

\[ \varepsilon_a = \frac{1}{3} \frac{K G_s \gamma_{\max} t R}{E_c I_c} \]

\[ \varepsilon_b = \frac{1}{6} \frac{K G_s \gamma_{\max} t R^2}{E_c I_c} \]

Mylonakis, Maravas, Taskari, Sextos (2016)
5. Classes of identical fragility

- Retrieve fragilities from the literature
- User-defined fragility
5. Classes of identical fragility

Classification of the critical components to fragility classes and values of the corresponding the $im_{mt}$ and $\beta_t$ parameters

<table>
<thead>
<tr>
<th>class ID</th>
<th>type</th>
<th>critical components</th>
<th>DS1</th>
<th>DS2</th>
<th>DS3</th>
<th>DS4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$im_{mt}$</td>
<td>$\beta_t$</td>
<td>$im_{mt}$</td>
<td>$\beta_t$</td>
</tr>
<tr>
<td>1 MSC Concrete</td>
<td>Bridge</td>
<td>cc1,cc7,cc10</td>
<td>0.16</td>
<td>0.70</td>
<td>0.53</td>
<td>0.70</td>
</tr>
<tr>
<td>2 MSSS Concrete</td>
<td>Bridge</td>
<td>cc3,cc4,cc5</td>
<td>0.22</td>
<td>0.80</td>
<td>0.69</td>
<td>0.80</td>
</tr>
<tr>
<td>3 Box MSSS Slab</td>
<td>Bridge</td>
<td>cc2,cc6</td>
<td>0.17</td>
<td>0.80</td>
<td>0.51</td>
<td>0.80</td>
</tr>
<tr>
<td>4 Standard</td>
<td>Tunnel</td>
<td>cc8,cc9</td>
<td>0.69</td>
<td>0.19</td>
<td>0.69</td>
<td>0.19</td>
</tr>
</tbody>
</table>
### 6. Repair cost and restoration times

<table>
<thead>
<tr>
<th>critical component ID</th>
<th>type</th>
<th>Traffic closure duration in days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DS1</td>
</tr>
<tr>
<td>cc1</td>
<td>Bridge</td>
<td>0</td>
</tr>
<tr>
<td>cc2</td>
<td>Bridge</td>
<td>0</td>
</tr>
<tr>
<td>cc3</td>
<td>Bridge</td>
<td>0</td>
</tr>
<tr>
<td>cc4</td>
<td>Bridge</td>
<td>0</td>
</tr>
<tr>
<td>cc5</td>
<td>Bridge</td>
<td>0</td>
</tr>
<tr>
<td>cc6</td>
<td>Bridge</td>
<td>0</td>
</tr>
<tr>
<td>cc7</td>
<td>Bridge</td>
<td>0</td>
</tr>
<tr>
<td>cc8</td>
<td>Tunnel</td>
<td>0</td>
</tr>
<tr>
<td>cc9</td>
<td>Tunnel</td>
<td>0</td>
</tr>
<tr>
<td>cc10</td>
<td>Bridge</td>
<td>0</td>
</tr>
</tbody>
</table>

Damage state dependent traffic closure times for each critical component of the network.
7. Seismic Hazard

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

\[
\lambda_{GM} (gm^*) = \sum \{ \int \int \int I [GM > gm^* | m, r, \varepsilon] \nu_i f_{M,R,E} (m, r, \varepsilon) \, dm \, dr \, d\varepsilon \} 
\]

\[
\nu_i f_{M,R,E} (m, r, \varepsilon) = \nu_i f_M (m | x_{hyp}) \, f_{x_{hyp}} (x_{hyp}) \, f_R (r | m, x_{hyp}, \theta_i) \, f_E (\varepsilon)
\]

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 \(x_{hyp}\)?
when this event occurs, what sort of rupture does it produce?
how likely are the possible GM values for this scenario?
7. Seismic Hazard

Geographical distribution of expected Intensity Measures

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

PGA (cm/sec²)  
PGV (cm/sec)

1x1km grid
7. Seismic Hazard

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

Monte Carlo simulation

Traffic flow redistribution given the network components functionality

\[
\bar{T}_r = \begin{cases} 
1 & \text{if } P_{i,k,m}[D \geq DS_2] \text{ and } im_{i,k,m} < 0.5 \\
0 & \text{if } P_{i,k,m}[D \geq DS_2] \text{ and } im_{i,k,m} \geq 0.5 
\end{cases}
\]
8a. Traffic analysis (pre-earthquake routes and flows)

Average Distance: 64,25km / Average Speed: 111,86km/h
8b. Traffic analysis for every seismic scenario

- K scenarios (50, 100, 475, 1000, 2000)
- M events (sources, IM spatial distribution)
- Monte Carlo with the P(component i to remain open | IM)
8c. Traffic analysis for every recovery phase

Seismic Hazard Level $k \in \{1, 2, \ldots, K\}$

$L$ seismic maps

$L$ probabilistic damage distributions

Probabilistic Damage Distribution $l \in \{1, 2, \ldots, L\}$

$S$ damage scenarios

Damage Scenario $s \in \{1, 2, \ldots, S\}$

Phase 1

Phase 2

Phase 3

Phase $P$
9. Network functionality vs. time

*Network Functionality* (a) is given by the sum of the importance factors of the links that are functional

\[
\alpha = 100 \cdot \sum \alpha_j
\]

\[
\alpha_j = \begin{cases} 
V_j & \text{if } j \text{ link is functional} \\
0 & \text{if } j \text{ link is non-functional}
\end{cases}
\]

A link is considered to be non-functional either when it is closed (due to damages) or if it is intact but does not serve to any travels
9. Network functionality vs. time

Traffic capacity over time for each scenario, source and restoration phase (as closed components gradually return to full function)
10. Earthquake induced direct & indirect cost

The total highway network cost due to seismic scenario \( k \) is defined as sum of the total structural cost and the total traffic cost:

\[
TNC_k = TSC_k + TTC_k
\]

every seismic scenario has a specific return period

\( TNC_k \) is the **estimated total network** cost corresponding to the return period of earthquake scenario \( k \)
10a. Earthquake induced indirect cost

\[
EC_p = D_p \cdot VOT
\]

\[
D_p = \sum_{j=1}^{M} (V_{jp} t_{jp} - V_{j0} t_{j0})
\]

- \(EC_p\): 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

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

\(t_{m,p}\): is the duration of phase \(p\) of traffic scenario \(m\)
10b. Earthquake induced direct (structural) cost

**DS – Repair Cost Ratio Index**

<table>
<thead>
<tr>
<th>Damage State</th>
<th>Repair-Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>No damage</td>
<td>0.00</td>
</tr>
<tr>
<td>Slight damage</td>
<td>0.03</td>
</tr>
<tr>
<td>Moderate damage</td>
<td>0.25</td>
</tr>
<tr>
<td>Major damage</td>
<td>0.75</td>
</tr>
<tr>
<td>Complete damage</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Structural Cost for critical component $i$:

$$\sum_{i=1}^{M} D_i = (RCR_{1i} P_{DS1i} + RCR_{2i} P_{DS2i} + RCR_{3i} P_{DS3i} + RCR_{4i} P_{DS4i}) \times TCC_i$$

- $M$ : 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
11. 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)

\[
ECO_p = \frac{\sum_{j=1}^{n_{tot}} (V_{j0} \cdot t_{j0})}{\sum_{j=1}^{n_{tot}} (V_{jp} \cdot t_{jp})}
\]

\[
ENV_p = \frac{\sum_{j=1}^{J} I_{j}}{\sum_{j=1}^{J} d_{jp} \cdot I_{j}}
\]

\[
CON_p = \frac{\sum_{z=1}^{S} (\gamma_{z} \cdot N_{k})}{\sum_{z=1}^{S} K_{z}}
\]
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10. Decision-making

Assessment of the “as-built” network

- Identify the critical seismic map per hazard level
- Spot critical key network components
- Plot time-variant indicators
- Calculate Resilience Indices
- Resilience Objectives are met?

Yes → END

No → Retrofit and strengthening of structural & geotechnical

Assessment of alternative resilience improvement strategies

- Additional traffic cost
- Days
- Functionality (100%)

NO →

- Retrofit the weak links
- Don’t Retrofit / Improve recovery plan
- Retrofit the links with the highest impact

No action
SHM and (nearly) Real-time Seismic Risk Assessment

Post-quake

Minimize implications on disaster response (immediate after) and recovery (in the long term)
12. Updating through SHM

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

(AFTER the earthquake based on structural monitoring & Shake Maps)
12. Updating through SHM: PGA & Sa(T1)
12. Updating through SHM: satellite link
12. Updating through SHM: satellite link
12. Updating through SHM: satellite link
1. Accelerometer

2. Deck acceleration data logger

Central power supply
1. UPS
   To the central power supply

2. Replacement battery of UPS

3. Power supply

4. Analog converter to ethernet

5. Modem to the local network

Data logger cable
Camera cable
Camera placement
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Real Time InterCity Seismic Risk
seismic risk in urban and interurban road networks.

www.retis-risk.eu

1,700 Km road
46 bridges and tunnels
28 km of tunnels
182 km of bridges
75 km of bridges