2nd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers

2η Προκήρυξη Ερευνητικών Έργων ΕΛ.Ι.Δ.Ε.Κ. για την Ενίσχυση Μεταδιδακτόρων Ερευνητών/τριών

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INFRARES

Towards resilient transportation infrastructure in a multi-hazard environment

Work Package:

WP6

Deliverable:

D6.1 - Guidelines for the fragility and loss assessment of transportation infrastructures considering soil-structure-interaction

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Deliverable D6.1

Guidelines for the fragility and loss assessment of transportation infrastructures considering soil-structure-interaction

Rev.	Comment	Prepared / Reviewed	Released
0	Final Issue	Grigorios Tsinidis, Sotiria Stefanidou, Anna Karatzetzou, Olga Markogiannaki	Grigorios Tsinidis

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1. Introduction

WP6 aims at disseminating the outcomes of the research project INFRARES (www.infrares.gr) to peers and the wider society, as well as at engaging Stakeholders, Operators and Consultancies that have an interest on risk and resilience assessment of transportation infrastructure in a multi-hazard environment. In particular, the objectives of WP6 are summarized as follows:

- Implementation of a dissemination plan for the outcomes of the project, which encompasses: (1) knowledge (proposal of a novel methodology for multiple hazard vulnerability assessment of transportation infrastructure); (2) end-products from research (development of a prototype software for risk and resilience analysis of transportation infrastructure), and (3) engagement of interested people (Stakeholders, Operators, Consultancies etc.).
- Delivery of technical guidelines and recommendations, concerning the risk and resilience assessment of transportation infrastructure subjected to combined effects of multiple natural hazards.
- Development of a web portal to advertise the outcomes of the project and engage interested people.

Deliverable D.6.1 is related to **Task 6.2: Drafting, of guidelines for the fragility and loss assessment of transportation infrastructures considering soil-structure-interaction effects.** The methodology for the resilience assessment of road bridges and tunnels under various single or multiple hazard scenarios, as well as *INFRARES software*, both developed within WP4 of INFRARES project, are presented in the form of guidelines allowing for an easy use by the end-users (such as governmental/public authorities and operators, stakeholders). The report includes the principals and methods for the fragility and resilience assessment of bridges and tunnels of transportation infrastructures, as well as examples of applications from the selected case study in Egnatia Motorway in Western Macedonia, Greece. The report accounts for invaluable comments of designers.

2. Resilience analysis framework

The methodology developed within INFRARES project for the resilience assessment of bridges and tunnels of road networks under various single or multiple hazard scenarios consists of four steps, i.e.:

- Step 1: identification of single or multiple hazard scenarios,
- Step 2: fragility analysis,
- Step 3: functionality estimation,
- Step 4: resilience quantification.

The flowcharts of the methodology referring to the resilience assessment of bridges and tunnels against single or multiple hazard scenarios are presented in Figure 1 and Figure 2, respectively.

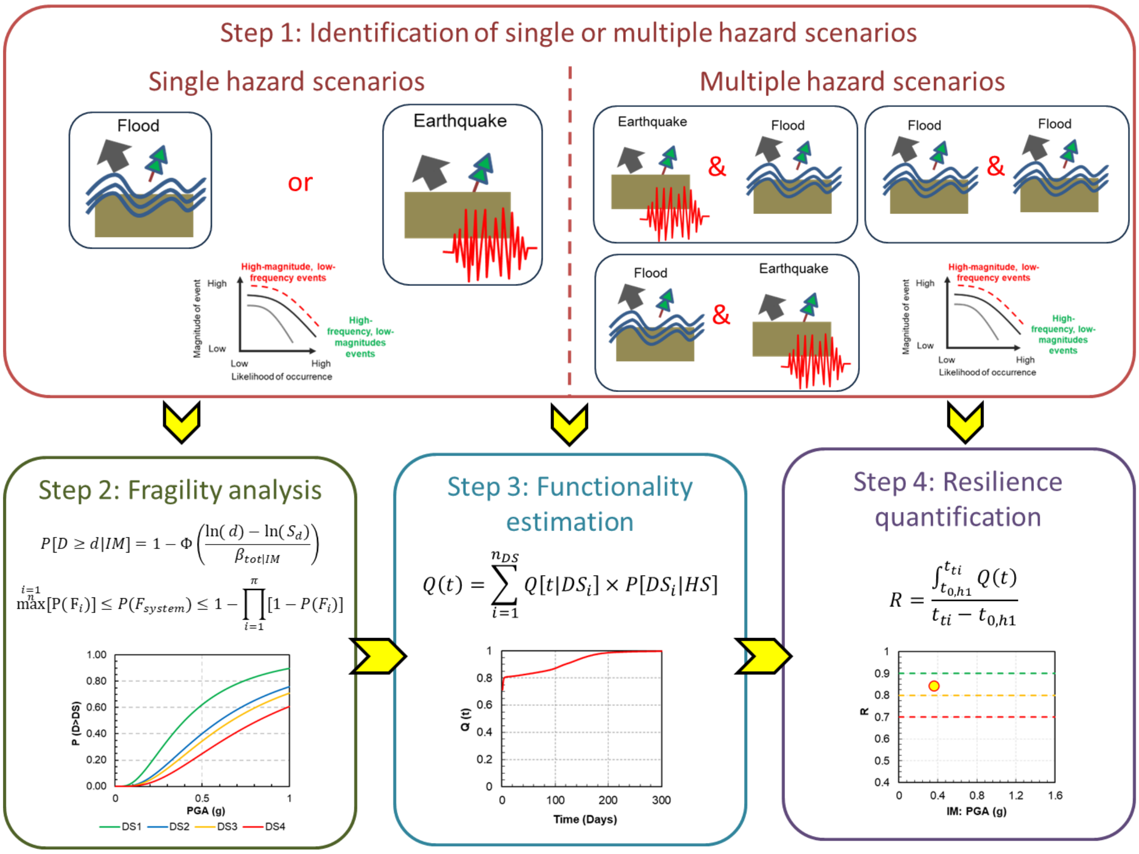


Figure 1: Framework for the resilience assessment of bridges against single or multiple natural hazards.

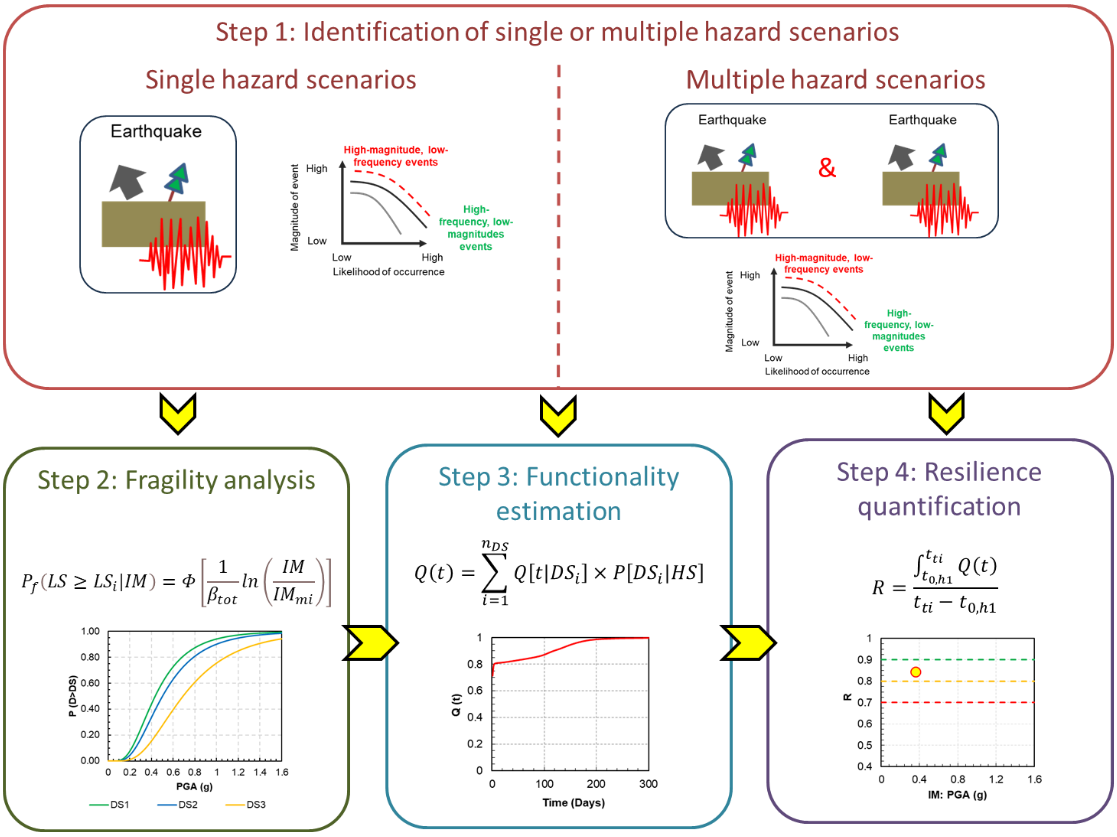


Figure 2: Framework for the resilience assessment of tunnels against single or multiple seismic events.

2.1 Identification of single or multiple hazard scenarios

The purpose of this step is to develop appropriate single and multiple hazard scenarios that will be considered in resilience assessment of the examined asset. In this project, seismic hazard, and flood hazard, were selected as the most critical natural hazards for the assessment of bridges and tunnels of road networks in Greece. Detailed frameworks were proposed within **WP1** of INFRARES project for the derivation of single seismic hazard or flood hazard scenarios for a region, as well as for multiple hazard scenarios (e.g., Figure 3). Details are provided in Karatzetzou et al. (2022). The application of these frameworks in Greece, resulted in detailed GIS-based maps, containing information regarding expected intensities of examined hazard(s) for various scenarios (i.e., various return periods). Examples of such maps are provided in Figure 4. Tables with ranges of intensities of hazards in multi-hazard scenarios were also provided (e.g., Table 1). The most representative hazard scenarios were introduced in INFRARES software.

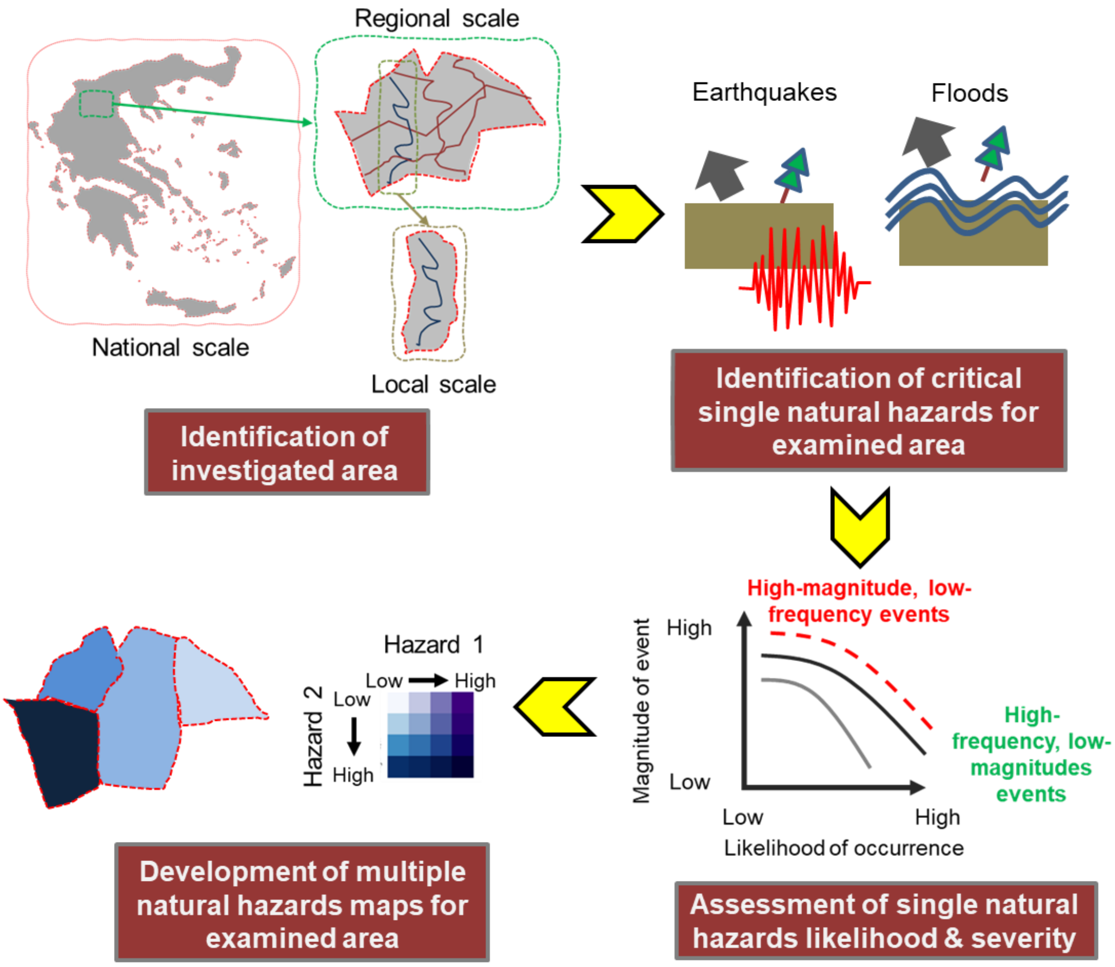
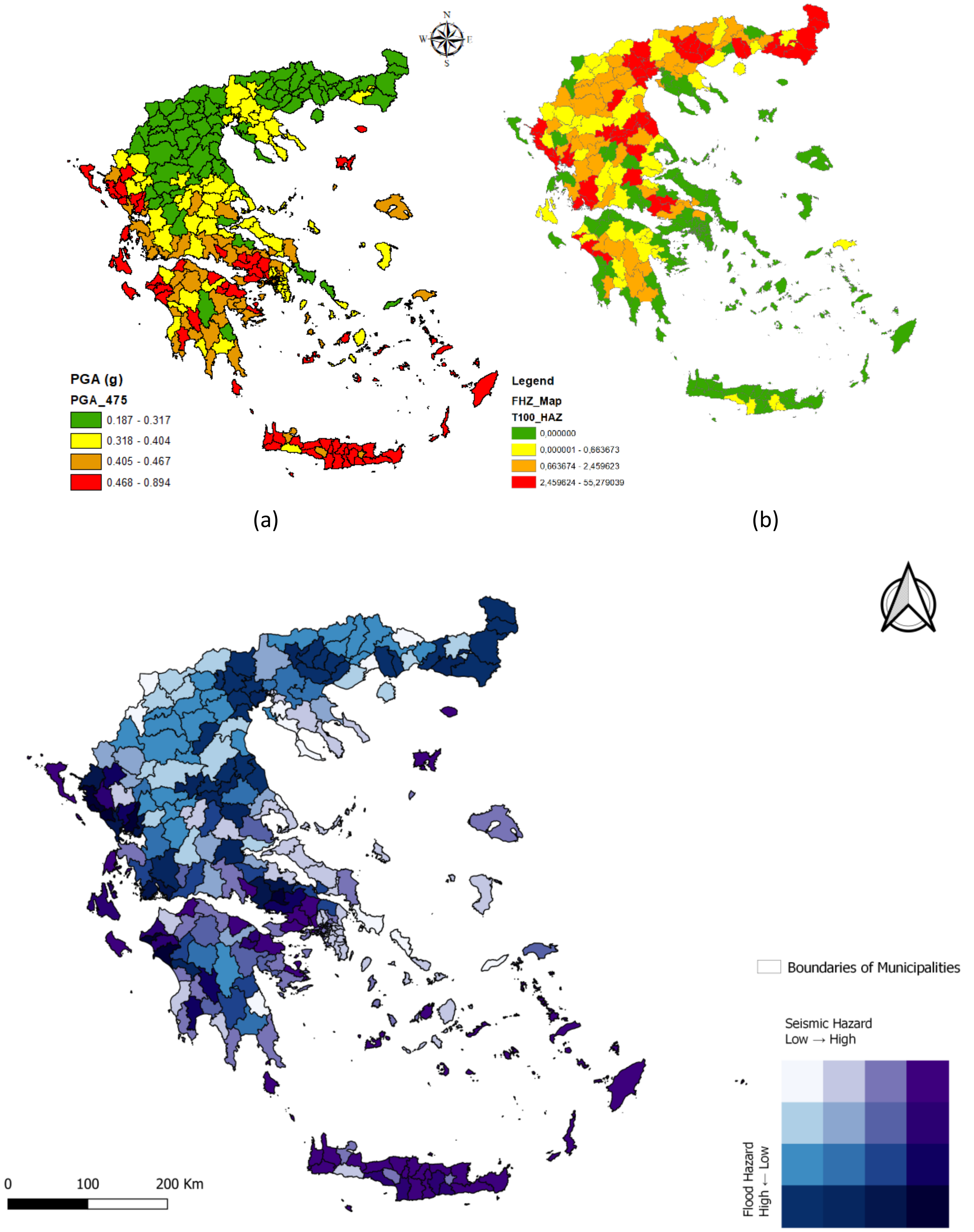


Figure 3. Steps for the development of multiple-hazard scenarios for the assessment of transportation infrastructure (e.g., road network) in a terrain.

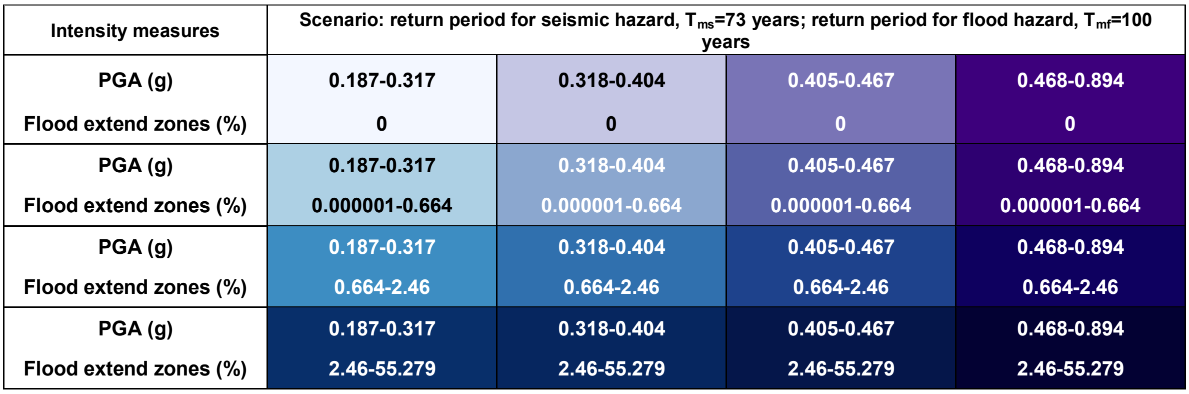


(a) (b)

(c)

Figure 4. (a) Seismic hazard maps for Greece for return period T_{ms}=475 years, (b) flood hazard map for Greece for return period T_{mf}=100 years, (c) bivariate map depicting the combination of seismic and flood hazard for Greece.

Table 1. Intensities for multi-hazard scenario with return period for seismic hazard, T_{ms}=475 years and return period for flood hazard, T_{mf}=100 years.

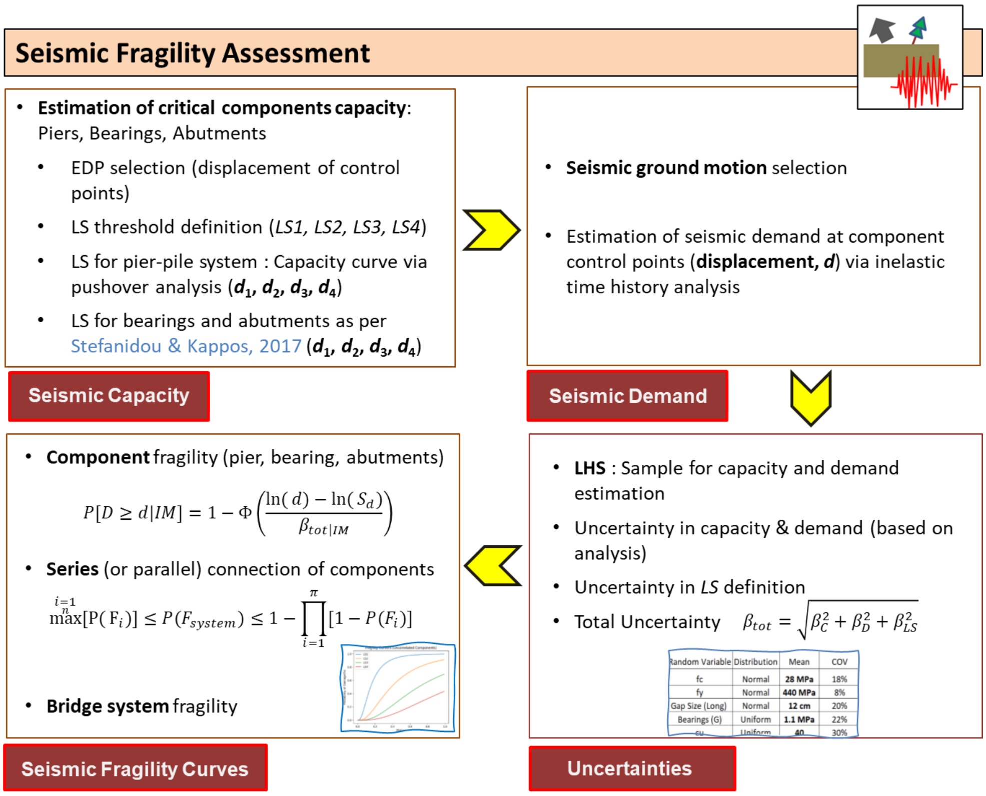


Intensity measures	Scenario: return period for seismic hazard, T_{ms}=73 years; return period for flood hazard, T_{mf}=100 years			
PGA (g)	0.187-0.317	0.318-0.404	0.405-0.467	0.468-0.894
Flood extend zones (%)	0	0	0	0
PGA (g)	0.187-0.317	0.318-0.404	0.405-0.467	0.468-0.894
Flood extend zones (%)	0.000001-0.664	0.000001-0.664	0.000001-0.664	0.000001-0.664
PGA (g)	0.187-0.317	0.318-0.404	0.405-0.467	0.468-0.894
Flood extend zones (%)	0.664-2.46	0.664-2.46	0.664-2.46	0.664-2.46
PGA (g)	0.187-0.317	0.318-0.404	0.405-0.467	0.468-0.894
Flood extend zones (%)	2.46-55.279	2.46-55.279	2.46-55.279	2.46-55.279

2.2 Fragility analysis

2.2.1 Bridges

Analytical frameworks for the fragility analysis of bridges under various single and multiple hazard scenarios (e.g., single seismic hazard, single flood hazard and combined seismic/flood hazards) were developed in the **WP2** of INFRARES project. Details are provided in Stefanidou et al. (2022). The methodology outline for seismic fragility assessment of bridges is summarised in Figure 5, whereas Figure 6 presents the methodology outline for flood fragility assessment of bridges, For the fragility assessment against multiple natural hazards, i.e., seismic and flood hazards, the same methodology is applied (Figure 7). Several scenarios of uncorrelated and different (separated in time) hazard events were developed for the derivation of system fragility functions. It should be outlined that the events were applied subsequently and, therefore, cumulative damage is considered in all examined multi-hazard scenarios. The application of the aforementioned frameworks on representative bridge systems, resulted in a series of fragility functions that were introduced in INFRARES software, as discussed in the following. Soil-structure interaction and ageing phenomena of the structure were considered in fragility analysis of examined systems (Stefanidou et al., 2022).



Seismic Fragility Assessment

- **Estimation of critical components capacity**: Piers, Bearings, Abutments
  - EDP selection (displacement of control points)
  - LS threshold definition (*LS1, LS2, LS3, LS4*)
  - LS for pier-pile system : Capacity curve via pushover analysis (d_1, d_2, d_3, d_4)
  - LS for bearings and abutments as per Stefanidou & Kappos, 2017 (d_1, d_2, d_3, d_4)

Seismic Capacity

- **Seismic ground motion** selection
- Estimation of seismic demand at component control points (**displacement, *d***) via inelastic time history analysis

Seismic Demand

- **Component** fragility (pier, bearing, abutments)

$$P[D \geq d|IM] = 1 - \Phi\left(\frac{\ln(d) - \ln(S_d)}{\beta_{tot|IM}}\right)$$

- **Series** (or parallel) connection of components

$$\overset{i=1}{\overset{n}{\max}}[\mathrm{P}(\mathrm{F}_i)] \leq P(F_{system}) \leq 1 - \prod_{i=1}^{\pi}[1 - P(F_i)]$$

- **Bridge system** fragility

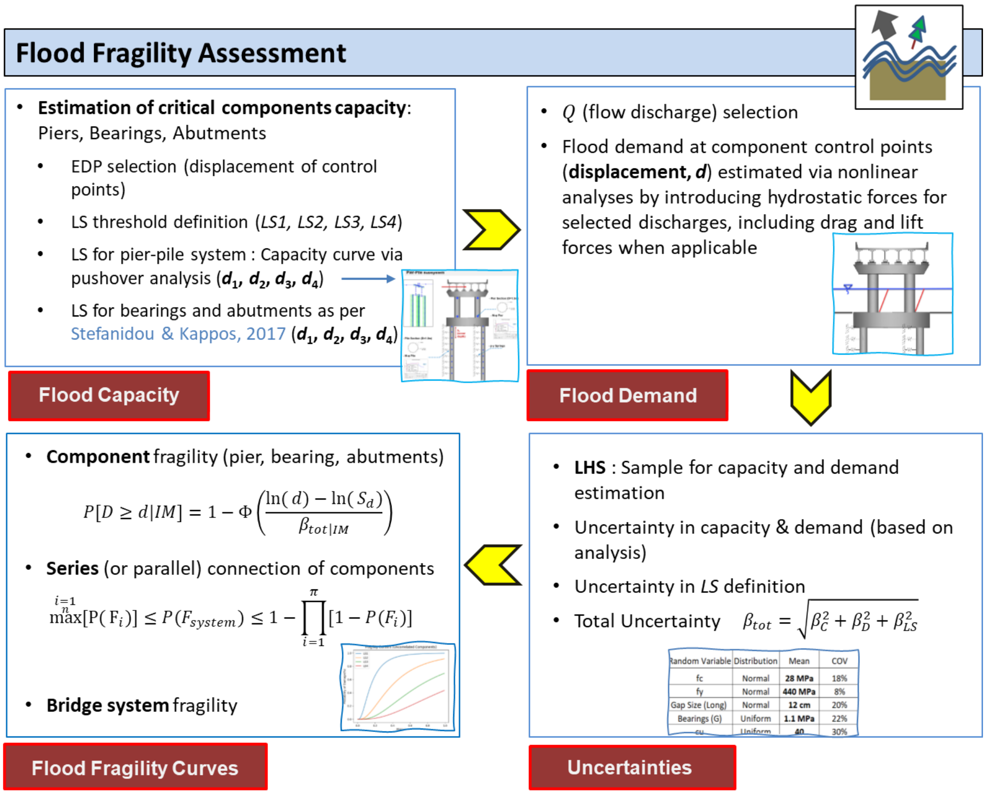
Seismic Fragility Curves

- **LHS** : Sample for capacity and demand estimation
- Uncertainty in capacity & demand (based on analysis)
- Uncertainty in *LS* definition
- Total Uncertainty $\beta_{tot} = \sqrt{\beta_C^2 + \beta_D^2 + \beta_{LS}^2}$

Random Variable	Distribution	Mean	COV
fc	Normal	**28 MPa**	18%
fy	Normal	**440 MPa**	8%
Gap Size (Long)	Normal	**12 cm**	20%
Bearings (G)	Uniform	**1.1 MPa**	22%
cu	Uniform	**40**	30%

Uncertainties

Figure 5: Methodology outline for seismic fragility assessment of bridges.



Flood Fragility Assessment

- **Estimation of critical components capacity**: Piers, Bearings, Abutments
  - EDP selection (displacement of control points)
  - LS threshold definition (*LS1, LS2, LS3, LS4*)
  - LS for pier-pile system : Capacity curve via pushover analysis (d_1, d_2, d_3, d_4)
  - LS for bearings and abutments as per Stefanidou & Kappos, 2017 (d_1, d_2, d_3, d_4)

Flood Capacity

- Q (flow discharge) selection
- Flood demand at component control points (**displacement, *d***) estimated via nonlinear analyses by introducing hydrostatic forces for selected discharges, including drag and lift forces when applicable

Flood Demand

- **Component** fragility (pier, bearing, abutments)

$$P[D \geq d|IM] = 1 - \Phi\left(\frac{\ln(d) - \ln(S_d)}{\beta_{tot|IM}}\right)$$

- **Series** (or parallel) connection of components

$$\overset{i=1}{\overset{n}{\max}}[\mathrm{P}(\mathrm{F}_i)] \leq P(F_{system}) \leq 1 - \prod_{i=1}^{\pi}[1 - P(F_i)]$$

- **Bridge system** fragility

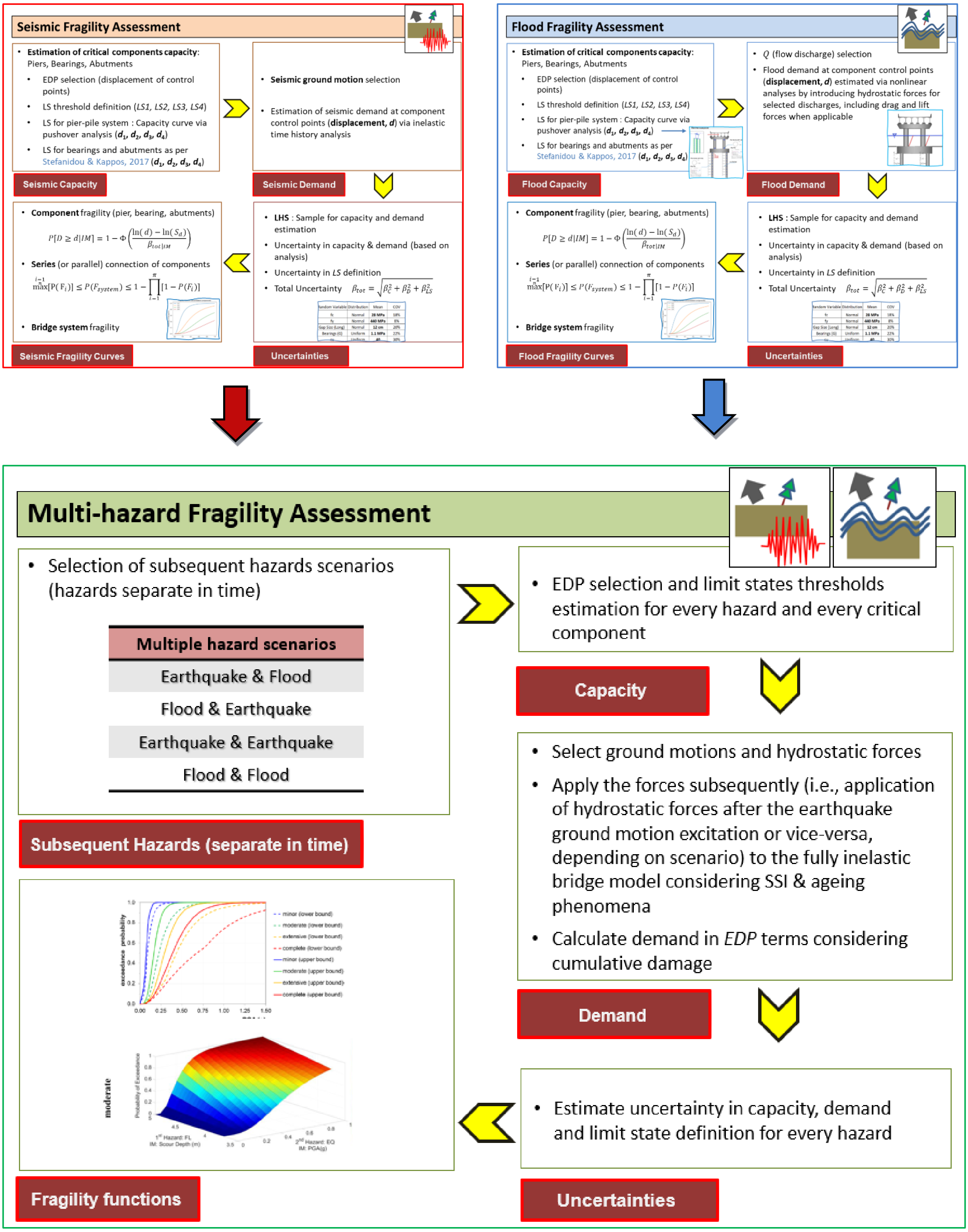
Flood Fragility Curves

- **LHS** : Sample for capacity and demand estimation
- Uncertainty in capacity & demand (based on analysis)
- Uncertainty in *LS* definition
- Total Uncertainty $\beta_{tot} = \sqrt{\beta_C^2 + \beta_D^2 + \beta_{LS}^2}$

Random Variable	Distribution	Mean	COV
fc	Normal	**28 MPa**	18%
fy	Normal	**440 MPa**	8%
Gap Size (Long)	Normal	**12 cm**	20%
Bearings (G)	Uniform	**1.1 MPa**	22%
cu	Uniform	**40**	30%

Uncertainties

Figure 6: Methodology outline for flood fragility assessment of bridges.



Seismic Fragility Assessment

- **Estimation of critical components capacity**: Piers, Bearings, Abutments
  - EDP selection (displacement of control points)
  - LS threshold definition (*LS1, LS2, LS3, LS4*)
  - LS for pier-pile system : Capacity curve via pushover analysis ($\boldsymbol{d_1, d_2, d_3, d_4}$)
  - LS for bearings and abutments as per Stefanidou & Kappos, 2017 ($\boldsymbol{d_1, d_2, d_3, d_4}$)

Seismic Capacity

- **Seismic ground motion** selection
- Estimation of seismic demand at component control points (**displacement, *d***) via inelastic time history analysis

Seismic Demand

- **LHS** : Sample for capacity and demand estimation
- Uncertainty in capacity & demand (based on analysis)
- Uncertainty in *LS* definition
- Total Uncertainty $\beta_{tot} = \sqrt{\beta_C^2 + \beta_D^2 + \beta_{LS}^2}$

Random Variable	Distribution	Mean	COV
fc	Normal	**28 MPa**	18%
fy	Normal	**440 MPa**	8%
Gap Size (Long)	Normal	**12 cm**	20%
Bearings (G)	Uniform	**1.1 MPa**	22%
cu	Uniform	**40**	30%

Uncertainties

- **Component** fragility (pier, bearing, abutments)

$$P[D \geq d|IM] = 1 - \Phi\left(\frac{\ln(d) - \ln(S_d)}{\beta_{tot|IM}}\right)$$

- **Series** (or parallel) connection of components

$$\max_{i=1}^{n}[\mathrm{P}(\mathrm{F}_i)] \leq P(F_{system}) \leq 1 - \prod_{i=1}^{\pi}[1 - P(F_i)]$$

- **Bridge system** fragility

Seismic Fragility Curves

Flood Fragility Assessment

- **Estimation of critical components capacity**: Piers, Bearings, Abutments
  - EDP selection (displacement of control points)
  - LS threshold definition (*LS1, LS2, LS3, LS4*)
  - LS for pier-pile system : Capacity curve via pushover analysis ($\boldsymbol{d_1, d_2, d_3, d_4}$)
  - LS for bearings and abutments as per Stefanidou & Kappos, 2017 ($\boldsymbol{d_1, d_2, d_3, d_4}$)

Flood Capacity

- Q (flow discharge) selection
- Flood demand at component control points (**displacement, *d***) estimated via nonlinear analyses by introducing hydrostatic forces for selected discharges, including drag and lift forces when applicable

Flood Demand

- **LHS** : Sample for capacity and demand estimation
- Uncertainty in capacity & demand (based on analysis)
- Uncertainty in *LS* definition
- Total Uncertainty $\beta_{tot} = \sqrt{\beta_C^2 + \beta_D^2 + \beta_{LS}^2}$

Random Variable	Distribution	Mean	COV
fc	Normal	**28 MPa**	18%
fy	Normal	**440 MPa**	8%
Gap Size (Long)	Normal	**12 cm**	20%
Bearings (G)	Uniform	**1.1 MPa**	22%
cu	Uniform	**40**	30%

Uncertainties

- **Component** fragility (pier, bearing, abutments)

$$P[D \geq d|IM] = 1 - \Phi\left(\frac{\ln(d) - \ln(S_d)}{\beta_{tot|IM}}\right)$$

- **Series** (or parallel) connection of components

$$\max_{i=1}^{n}[\mathrm{P}(\mathrm{F}_i)] \leq P(F_{system}) \leq 1 - \prod_{i=1}^{\pi}[1 - P(F_i)]$$

- **Bridge system** fragility

Flood Fragility Curves

Multi-hazard Fragility Assessment

- Selection of subsequent hazards scenarios (hazards separate in time)

Multiple hazard scenarios
Earthquake & Flood
Flood & Earthquake
Earthquake & Earthquake
Flood & Flood

Subsequent Hazards (separate in time)

- EDP selection and limit states thresholds estimation for every hazard and every critical component

Capacity

- Select ground motions and hydrostatic forces
- Apply the forces subsequently (i.e., application of hydrostatic forces after the earthquake ground motion excitation or vice-versa, depending on scenario) to the fully inelastic bridge model considering SSI & ageing phenomena
- Calculate demand in *EDP* terms considering cumulative damage

Demand

- Estimate uncertainty in capacity, demand and limit state definition for every hazard

Uncertainties

Fragility functions

Figure 7: Methodology outline for seismic, flood and multiple hazard fragility assessment of bridges.

2.2.2 Tunnels

Analytical frameworks for the fragility analysis of tunnels under various single and multiple hazard scenarios (e.g., single seismic hazard and combined seismic/seismic hazards) were developed in the **WP3** of INFRARES project. Details are provided in Tsinidis et al. (2023). The methodology outline for fragility assessment of tunnels subjected to ground shaking is presented in Figure 8, whereas Figure 9 presents the methodology outline for the assessment of tunnels, subjected to fault dislocation. The application of the aforementioned frameworks, resulted in a series of fragility functions that were introduced in INFRARES software, as discussed in the following. Soil-structure interaction and ageing phenomena of the tunnel were considered in fragility analysis of examined systems (Tsinidis et al. 2023).

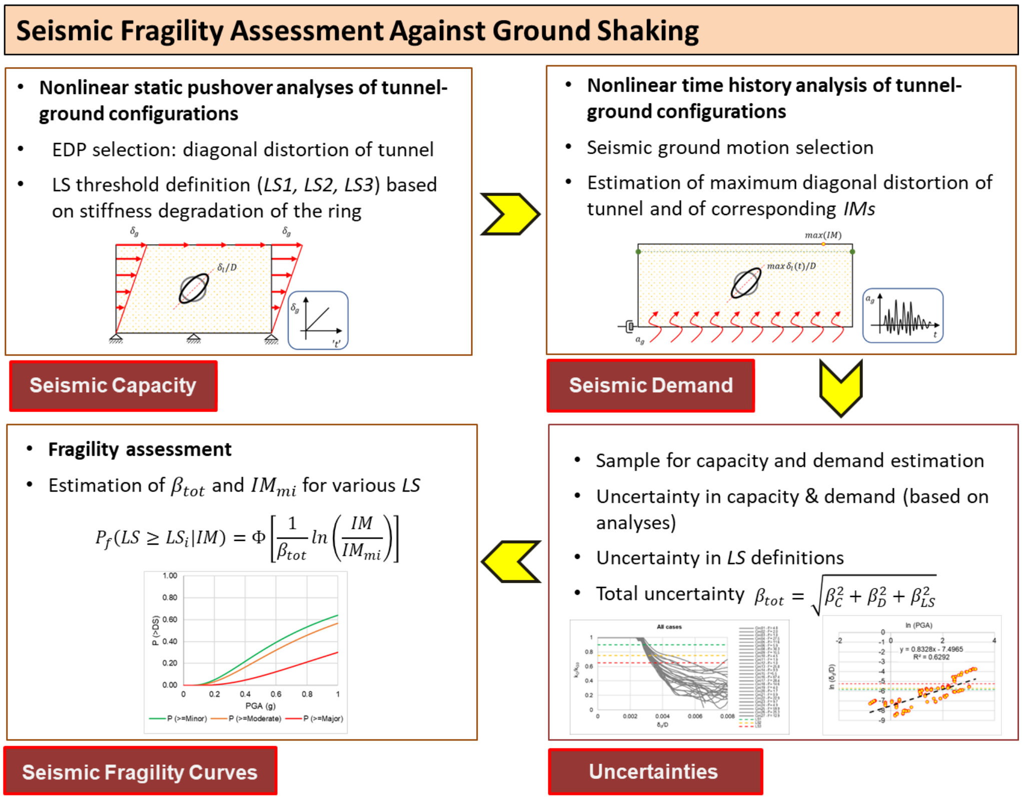
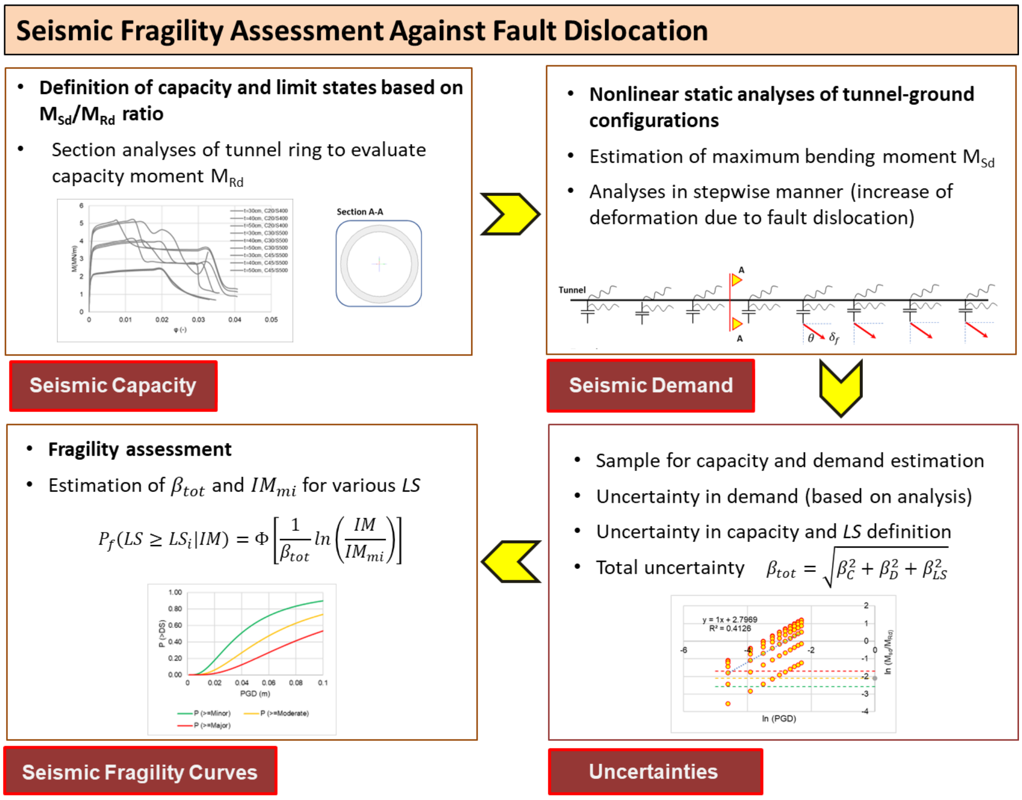


Figure 8: Outline of the analytical framework for seismic fragility assessment of tunnels against ground seismic shaking, acting in the transverse direction.



Seismic Fragility Assessment Against Fault Dislocation

- **Definition of capacity and limit states based on M_{Sd}/M_{Rd} ratio**
- Section analyses of tunnel ring to evaluate capacity moment M_{Rd}

Seismic Capacity

- **Nonlinear static analyses of tunnel-ground configurations**
- Estimation of maximum bending moment M_{Sd}
- Analyses in stepwise manner (increase of deformation due to fault dislocation)

Seismic Demand

- Sample for capacity and demand estimation
- Uncertainty in demand (based on analysis)
- Uncertainty in capacity and *LS* definition
- Total uncertainty $\beta_{tot} = \sqrt{\beta_C^2 + \beta_D^2 + \beta_{LS}^2}$

Uncertainties

- **Fragility assessment**
- Estimation of β_{tot} and IM_{mi} for various *LS*

$$P_f(LS \geq LS_i|IM) = \Phi\left[\frac{1}{\beta_{tot}} ln\left(\frac{IM}{IM_{mi}}\right)\right]$$

Seismic Fragility Curves

Figure 9: Outline of analytical framework for seismic fragility assessment of tunnels against fault dislocation.

2.3 Functionality estimation

Functionality is estimated immediately after an extreme event, as well as at different time steps during the retrofit/restoration phase of the examined asset (bridge or tunnel), based on the following equation:

$$Q(t) = \sum_{i=1}^{n_{DS}} Q[t|DS_i] \times P[DS_i|HS], \qquad t_{0,h1} \leq t \leq t_{ti} \quad (1)$$

where $Q(t)$ is the functionality level of the examined asset at time t (after the event) for a selected hazard scenario (HS) (single or multiple), n_{DS} is the number of damage (limit) states used in fragility analysis, and $Q[t|DS_i]$ is the functionality level of the asset when being at damage state DS_i (defined based on adopted restoration models). t_{ti} is the time in the restoration process that is investigated, and $t_{0,h1}$ is the time that the hazard occurs (single or the second hazard in case of multi-hazard scenario). $P[DS_i|HS]$ represents the probability of occurrence of damage state DS_i, computed using the fragility functions for a given IM level, as defined in the following equations:

$$\left.\begin{array}{c} P[DS_i|IM] = P[DS > DS_{i+1}|IM] - P[DS > DS_i|IM] \quad when\ i = 0,1,\ldots,n_{DS}-1 \\ P[DS_i|IM] = P[DS > DS_i|IM] \quad when\ i = n_{DS} \end{array}\right\} (2)$$

where $P[DS > DS_i|IM]$ is obtained from the selected fragility functions. $P[DS > DS_0|IM]$ is the probability of no damage state after the event, hence in Equation (1) is multiplied by unity (1), that represents a full functionality. To estimate functionality, restoration functions required.

2.3.1 Recovery curves for bridges

The restoration functions proposed by HAZUS (HAZUS, 2020) for the seismic resilience assessment bridges were considered herein (Figure 10 and Table 2). In case of flood hazard, the restoration curves proposed by Argyroudis et al. (2020) were adopted (Figure 11 and Table 3).

Table 2. Functionality levels of bridges after an earthquake event (HAZUS, 2020).

Limit State	Functionality									
	1 day	3 days	7 days	30 days	90 days	125 days	200 days	450 days	500 days	600 days
DS1: Slight damage	0.7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DS2: Moderate damage	0.3	0.6	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DS3: Extensive damage	0.02	0.05	0.06	0.15	0.65	1.00	1.00	1.00	1.00	1.00
DS4: Complete damage	0	0.02	0.02	0.04	0.1	0.3	0.9	1.00	1.00	1.00

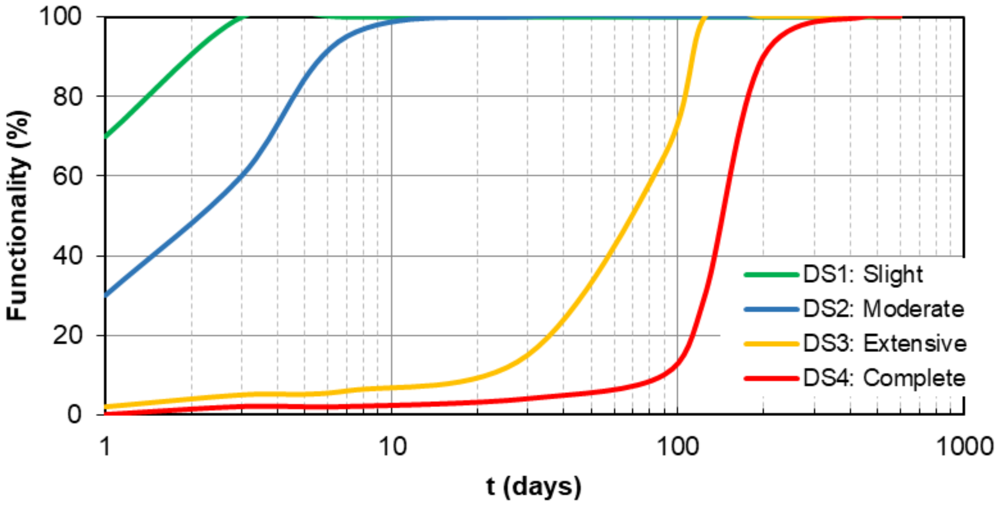


Figure 10: Recovery curves for bridges after an earthquake event (HAZUS, 2020).

For the analysis cases, where subsequent natural hazards are considered in the resilience assessment of the examined bridge (i.e., multi-hazard scenarios, for instance, earthquake followed by a flood or flood followed by flood etc.), it is assumed that no restoration has started after the first hazard event (for instance, the events have limited time difference). This assumption is considered as the most critical for the assessment of road networks and is valid for low to medium levels of damage caused by the first hazard event on the examined asset (bridge). Indeed, in these cases the functionality of the asset reduces (compared to the initial pre-event state); however, the asset may remain operable. When the first hazard event leads to high levels of damage or even collapse, it is evident that the resilience assessment of the asset after a subsequent independent natural hazard event makes no sense if no restoration work has been conducted before the latter event. Based on the above assumptions, the same restoration functions as those selected for single hazard assessment were employed in case of multiple hazard scenarios, with the selection of the functions being based on the latter hazard event. It is worth noting that in cases of multiple hazard scenarios, the effects of the damage caused by the first natural hazard were explicitly accounted for in the resilience analysis by employing relevant fragility functions in the fragility analysis step, as discussed above (i.e., fragility curves that account the cumulative effects of both hazards).

Table 3. Functionality levels of bridges after a flood event (Argyroudis et al., 2020).

Limit State	**Functionality**									
	1 day	**3 days**	**7 days**	**30 days**	**90 days**	**125 days**	**200 days**	**450 days**	**500 days**	**600 days**
DS1: Slight damage	0.24	0.32	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DS2: Moderate damage	0.15	0.19	0.28	0.87	1.00	1.00	1.00	1.00	1.00	1.00
DS3: Extensive damage	0.05	0.07	0.10	0.50	1.00	1.00	1.00	1.00	1.00	1.00
DS4: Complete damage	0.01	0.01	0.01	0.02	0.08	0.17	0.50	1.00	1.00	1.00

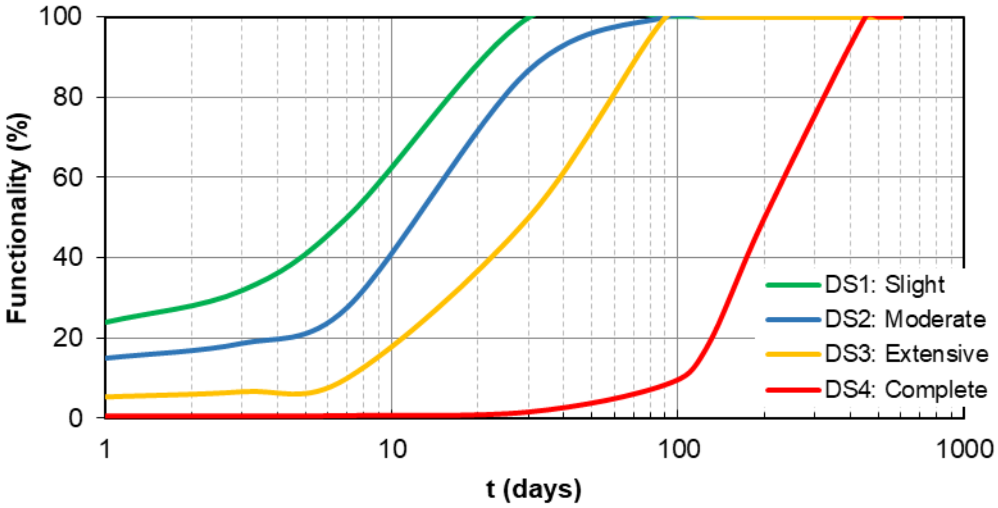


Figure 11: Recovery curves for bridges after a flood event (Argyroudis et al., 2020).

2.3.2 Recovery curves for tunnels

The functionality is estimated as per Equations 1 and 2 for various time steps after the earthquake event (in case of single hazard scenario) or events (in case of multiple hazards scenario). In the latter case, the analysis is conducted assuming that no restoration has started after the first earthquake event, following the same assumptions as for bridges. Due to the lack of reliable data referring to restoration of tunnels of road networks in Greece, the restoration functions proposed by HAZUS (HAZUS, 2020) are considered herein (Figure 12 and Table 4).

Table 4. Functionality levels of tunnels after an earthquake event (HAZUS, 2020).

Limit State	**Functionality**									
	1 day	**3 days**	**7 days**	**30 days**	**90 days**	**125 days**	**200 days**	**450 days**	**500 days**	**600 days**
DS1: Slight damage	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DS2: Moderate damage	0.25	0.65	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DS3: Extensive damage	0.05	0.08	0.10	0.30	0.95	1.00	1.00	1.00	1.00	1.00
DS4: Complete damage	0.00	0.03	0.03	0.05	0.15	0.30	0.90	1.00	1.00	1.00

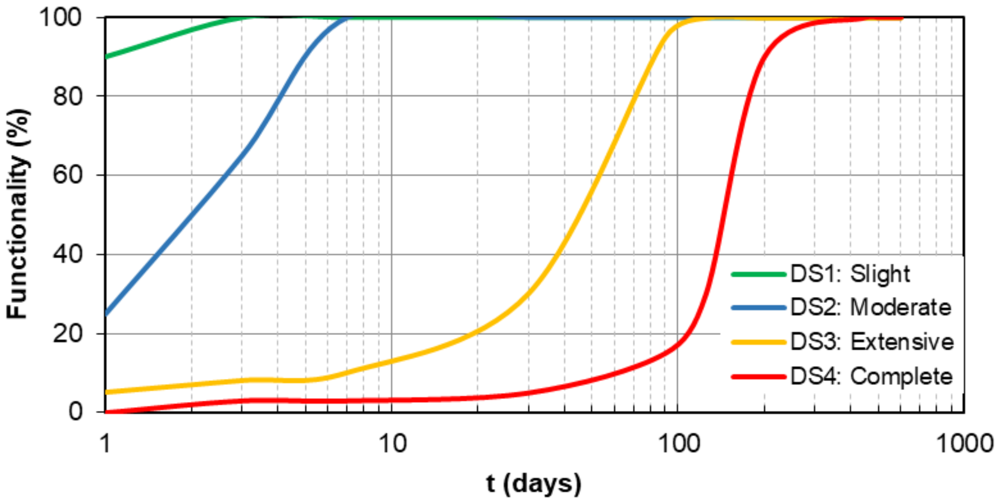


Figure 12: Recovery curves for tunnels after an earthquake event (HAZUS, 2020).

2.4 Quantification of resilience

In this final step, the results of the fragility assessment, the functionality losses, the estimated duration for repairs and the recovery process to restore functionality are combined to quantify the resilience of the bridge against single or multi-hazard scenarios. A resilience index R is introduced for this purpose, calculated as:

$$R = \frac{\int_{t_o}^{t_h} Q(t)}{t_h - t_o} \quad (3)$$

where: $Q(t)$ is the functionality level at the time t, t_t is the time in the restoration process that is investigated, t_0 is the time that the natural hazard event occurs. In case of multiple hazard analysis t_0 refers to the time when the second hazard event occurs.

To facilitate decision-making processes referring to retrofit actions, prioritization of actions to minimize risk and potential losses, as well as for post-event risk management, a *resilience grade* is set, by introducing quantitative thresholds to the resilience index, R, as shown in Table 5.

Table 5. Resilience grade for the assessment of bridges subjected to single or multiple hazard scenarios.

Grade	Range	Colour
High Resilience	$0.9 \leq R < 1.0$	Green
Relatively High Resilience	$0.8 \leq R < 0.9$	Yellow
Moderate Resilience	$0.7 \leq R < 0.8$	Orange
Low Resilience	$R < 0.7$	Red

3. INFRARES software

The methodology presented in section 2 was introduced in *INFRARES software*, a VBA-based software, developed in Excel to allow for easy implementation. The software uses an ArcGIS Add-in, allowing for a plot of the outcome of the resilience analysis of the examined asset (i.e., resilience index R and resilience grade of the bridge or tunnel) on its actual location on the network. The software requires six types of *input data*, which are used to conduct the resilience analysis. Executing the program, the software returns the *resilience index* R for the examined asset (bridge/tunnel) and examined hazard scenario. All input data and the output are described in detail in the following sections.

3.1 Input data

The data that the user is asked to enter in INFRARES software are the following:

1. **"ASSET Name"**: The name of the examined asset (e.g., name of bridge).
2. **"Municipality"**: The Municipality name in which the examined asset (bridge or tunnel) is located.
3. **"Type"**: The type of the examined asset (bridge or tunnel).
4. **"Case"**: The natural hazard scenario.

If "**Bridge**" is selected, the following natural hazard scenarios are available:

   a. "**Single Event: EQ**": a single earthquake event is considered in the analysis.
   b. "**Multi Event: EQ-Flood**": a multiple hazard scenario consisting of an earthquake event followed by a flood event is considered in the analysis.
   c. "**Multi Event: Flood-EQ**": a multiple hazard scenario consisting of a flood event followed by an earthquake event is considered in the analysis.
   d. "**Multi Event: Flood-Flood**": a multiple hazard scenario consisting of a flood event followed by an independent flood event is considered in the analysis.

If "**Tunnel**" is selected, the following natural hazard scenarios are available:

   a. "**Single Event: EQ**": a single earthquake event is considered in the analysis.
   b. "**Multi Event: EQ-EQ**": a multiple hazard scenario consisting of an earthquake event followed by an independent earthquake event is considered in the analysis.

5. "**Bridge Type**": The selection appears if "Bridge" is selected as the type of the examined asset; the following selections are available:

a. "**332**": The fragility functions, developed within INFRARES project for bridges with decks of precast-prestressed beams, simply-supported through bearings to multi-column piers, are employed in the analysis.

b. "**232**": The fragility functions, developed within INFRARES project for bridges with decks of precast-prestressed beams, simply-supported through bearings to hollow rectangular piers, are employed in the analysis.

c. "**User defined**": User defined fragility functions are employed in the analysis; additional cells are activated upon selection to add the parameters for the definition of fragility functions based on Equation 1.

$$P_f(DS \geq DS_i|IM) = \Phi\left[\frac{1}{\beta_{tot}} ln\left(\frac{IM}{IM_{mi}}\right)\right] \quad (1)$$

where $P_f(DS \geq DS_i|IM)$ is the probability of exceeding a given limit state, for a given level of intensity of the hazard (the latter expressed via an IM), Φ is the standard cumulative probability function, IM_{mi} is the median threshold value of the intensity measure, required to cause the ith limit state and β_{tot} is the total lognormal standard deviation, describing uncertainties (both aleatory and epistemic) related with the definition of the fragility function; β_{tot} and IM_{mi} should be defined; up to three damage states may be employed in fragility functions definition.

It should be mentioned that the damage states of the fragility curves developed within INFRARES project read as follows:

- DS1: minor damage;
- DS2: moderate damage;
- DS3: major/significant damage;
- DS4: significant damage/collapse.

6. "**Soil Type**": The selection appears if "Tunnel" is selected as the type of the examined asset; the following selections are available:

a. "B": The fragility functions, developed within INFRARES project for circular tunnels embedded in soil class B acc. to EN1998-1-1, are employed in the analysis.

b. "C": The fragility functions, developed within INFRARES project for circular tunnels embedded in soil class C acc. to EN1998-1-1, are employed in the analysis.

c. "D": The fragility functions, developed within INFRARES project for circular tunnels embedded in soil class D acc. to EN1998-1-1, are employed in the analysis.

d. "User defined": User defined fragility functions are employed in the analysis; additional cells are activated upon selection to add the parameters for the definition of fragility functions based again on Equation 2.

$$P_f(DS \geq DS_i|IM) = \Phi\left[\frac{1}{\beta_{tot}} ln\left(\frac{IM}{IM_{mi}}\right)\right] \quad (2)$$

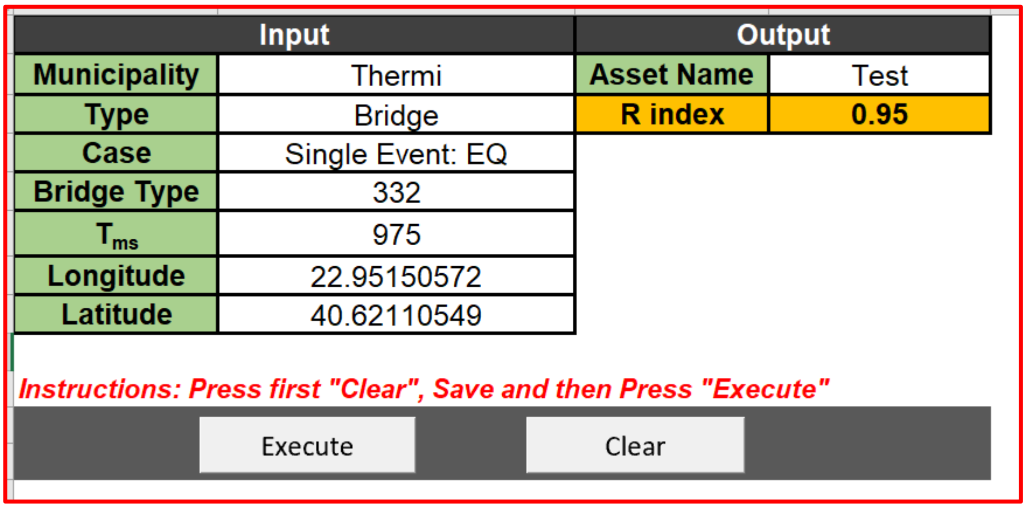
where $P_f(DS \geq DS_i|IM)$ is the probability of exceeding a given limit state, for a given level of intensity of the hazard (the latter expressed via an IM), Φ is the standard cumulative probability function, IM_{mi} is the median threshold value of the intensity measure, required to cause the ith limit state and β_{tot} is the total lognormal standard deviation, describing uncertainties (both aleatory and epistemic) related with the definition of the fragility function; β_{tot} and IM_{mi} should be defined; up to three damage states may be employed in fragility functions definition.

The damage states of the fragility curves developed within INFRARES project read as follows:

- DS1: minor damage;
- DS2: moderate damage;
- DS3: major/significant damage.

7. "**T_{ms}**": The return period of the seismic scenario is defined for the analysis referring to seismic hazard (the selection affects the intensity of the adopted seismic scenario, as per Maps provided in Annex B of instructions tab); the following selections are available:
    a. "73": Seismic scenario refers to a return period of 73 years.
    b. "102": Seismic scenario refers to a return period of 102 years.
    c. "475": Seismic scenario refers to a return period of 475 years.
    d. "975": Seismic scenario refers to a return period of 975 years .
8. "**Longitude**": The longitude of the location of the examined asset is defined.
9. "**Latitude**": The latitude of the location of the examined asset is defined.
10. "**Clear**": The selection clears all graphs depicted on tab and resets resilience index R back to zero.
11. "**Execute**": The selection executes the program, based on the data provided and returns the output data.
12.

Figure 13 shows the environment where the user is prompted to enter the input data. A series of drop-down lists appear depending on the selections of the User to complete the input data required in the analysis.



Input	
Municipality	Thermi
Type	Bridge
Case	Single Event: EQ
Bridge Type	332
T_{ms}	975
Longitude	22.95150572
Latitude	40.62110549

Output	
Asset Name	Test
R index	0.95

Instructions: Press first "Clear", Save and then Press "Execute"

Figure 13: Data entry environment of INFRARES software.

3.2 Output data

Once the program is executed, the user has the following output data available: (a) a graph with the fragility functions selected and employed in the analysis; (b) a graph of the resilience curve showing the evolution of the recovery of functionality with time (in days) and (c) a graph of the resilience index, plotted against the adopted value of the intensity measure of examined seismic hazard (in case of two hazards, the intensity measure of the last hazard is plotted); a resilience grade is also provided (i.e., high resilience $0.9 \leq R \leq 1$, relatively high resilience $0.8 \leq R \leq 0.9$, moderate resilience $0.7 \leq R \leq 0.8$, low resilience $R < 0.7$) (see Table 5), and (d) the "R index" value.

To depict the results of analysis on an ArcGIS map, ArcGIS Add-in should be downloaded via the following link:

https://pages.store.office.com/addinsinstallpage.aspx?assetid=WA200004179&rs=en-US&correlationId=ff597f4a-c9fd-8bb9-c83d-a67cab9b3fd7

and installed in Excel as per provided instructions (in download page). After installation the ArcGIS tool will appear on the right-hand side of the Excel sheets. The User may continue by using the *'access public content'* option provided by ArcGIS Add-in. By selecting this option, a GIS map will appear. If the results of analysis are not displayed immediately (e.g., during first run of the software), the User may proceed by selecting the *'Layers'* tab in ArcGIS tool. Selecting the *'+Excel'* option that appears on the left bottom of the window, the output of analysis will automatically appear.

Detailed instructions on how to use the software are provided in the tab named 'INSTRUCTIONS', whereas the input data, as well as the results of the analysis are provided in the tab named 'SOFTWARE-RESILIENCE'. Figure 14 Illustrates a representative part of the INSTRUCTIONS tab, whereas Figure 15 portrays an example of what the user will see in the main analysis tab, i.e., 'SOFTWARE-RESILIENCE' tab.

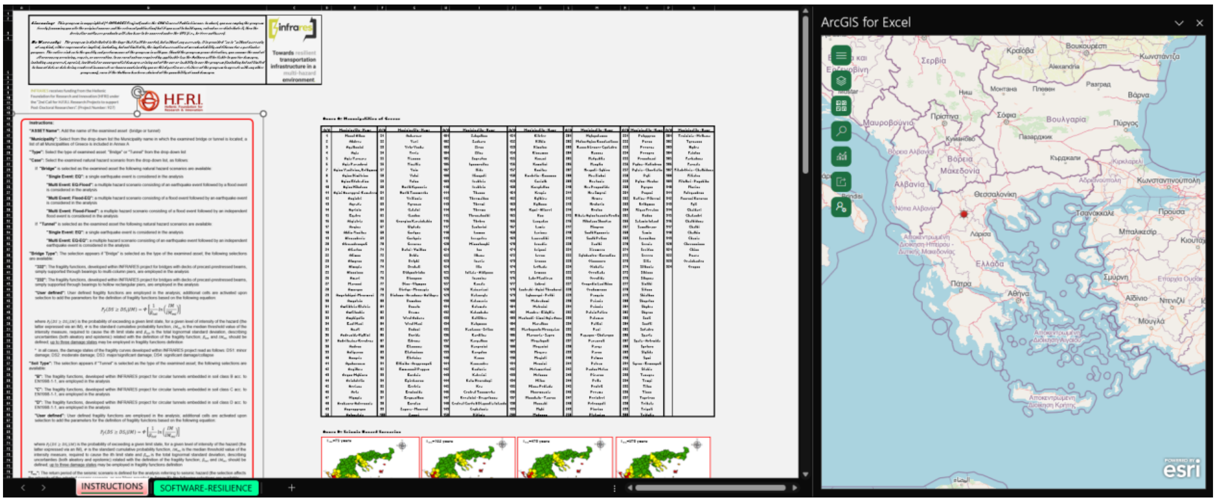
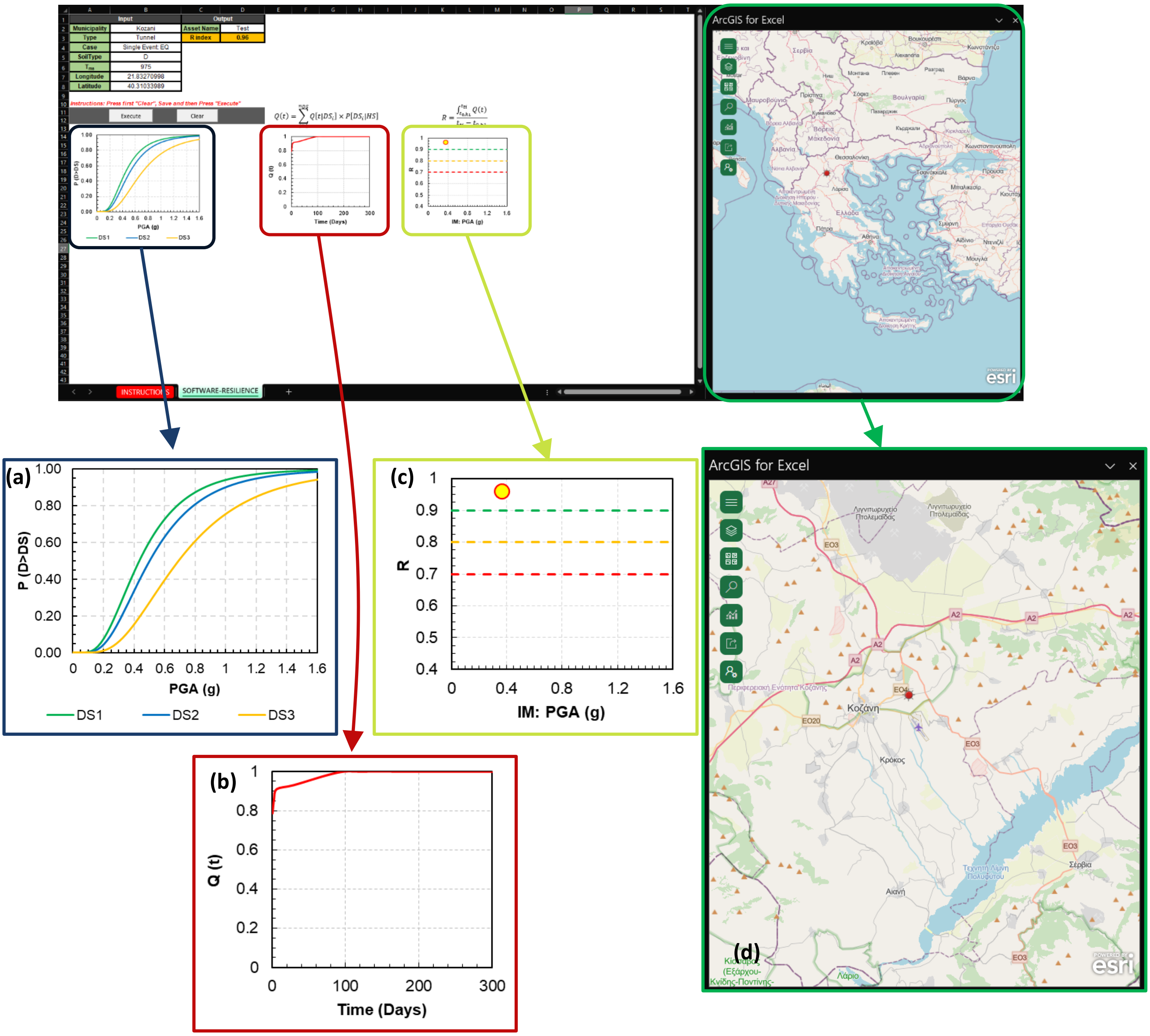


Figure 14: Snapshot of tab 'INSTRUCTIONS'.



Input		Output	
Municipality	Kozani	Asset Name	Test
Type	Tunnel	R index	0.96
Case	Single Event: EQ		
SoilType	D		
T_m	975		
Longitude	21.83270998		
Latitude	40.31033989		

Instructions: Press first "Clear", Save and then Press "Execute"

$$Q(t) = \sum^{nDS} Q[t|DS_i] \times P[DS_i|HS]$$

$$R = \frac{\int_{t_{0,h1}}^{t_{ri}} Q(t)}{t_{ri} - t_{0,h1}}$$

Figure 15: Snapshot of tab 'RESILIENCE-SOFTWARE'; (a) fragility curves, (b) resilience curve, (c) resilience index, (d) GIS map.

4. Application examples

4.1 Application on Kalogirou Bridge

4.1.1 Bridge description

Kalogirou bridge, a simply supported bridge selected as the first case study, is a river crossing bridge in Egnatia Motorway located within the region of Western Macedonia (Figure 16). Kalogirou bridge is a concrete bridge with seven equal spans and a total length of $240\ m$. The deck consists of an $11\ m$ wide top slab on simply supported precast-prestressed beams with continuity in the top slab over the piers; the beams are supported on elastomeric bearings. The piers have a hollow rectangular cross-section ($5.50\ m \times 2.75\ m$, with $0.30\ m$ thick walls) and heights varying from $21.0\ m$ to 50.6 . Shorter piers rest on shallow foundation and taller piers on pile foundation. The bridge piers located at the river basin have pile foundation. The deck ends are supported on seat-type abutments through elastomeric bearings, while joints of $100\ mm$ and $150\ mm$ width separate the deck from the abutment in the longitudinal and the transverse direction, respectively.

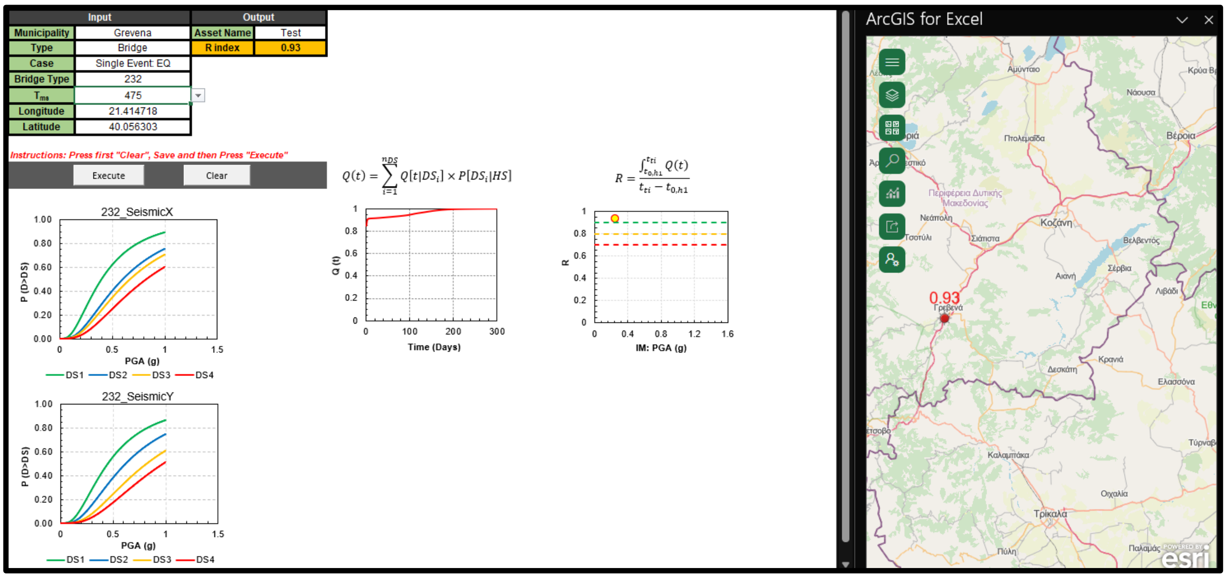
Figure 16: Kalogirou bridge.

4.1.2 Resilience assessment

INFRARES software is used to apply the methodology. The selected bridge corresponds to bridge category #232. The fragility curves developed in WP2 of INFRARES project (Stefanidou et al., 2022) for the assessment of bridges against single or multiple hazard events are employed in the analysis.

The results from the INFRARES software application for selected single and multiple hazard scenarios are provided in Figure 17 to Figure 19.

- **Single Event : Earthquake (EQ), return period T_{ms}= 475 years**



Input		Output	
Municipality	Grevena	Asset Name	Test
Type	Bridge	R index	0.93
Case	Single Event: EQ		
Bridge Type	232		
T_{ms}	475		
Longitude	21.414718		
Latitude	40.056303		

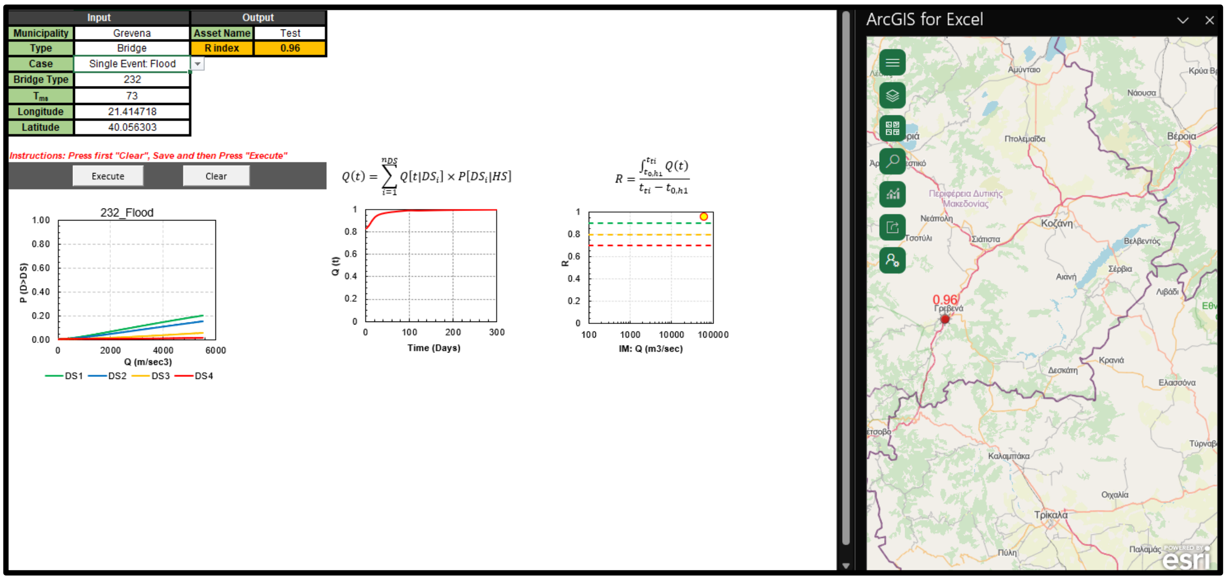
Instructions: Press first "Clear", Save and then Press "Execute"

$$Q(t) = \sum_{i=1}^{nDS} Q[t|DS_i] \times P[DS_i|HS]$$

$$R = \frac{\int_{t_{0,h1}}^{t_{ri}} Q(t)}{t_{ri} - t_{0,h1}}$$

Figure 17: Resilience analysis of Kalogirou bridge (bridge category #232) for an earthquake event with T_{ms}=475 years.

- **Single Event : Flood (FL), return period T_{mf}= 100 years**



Input		Output	
Municipality	Grevena	Asset Name	Test
Type	Bridge	R index	0.96
Case	Single Event: Flood		
Bridge Type	232		
T_{ms}	73		
Longitude	21.414718		
Latitude	40.056303		

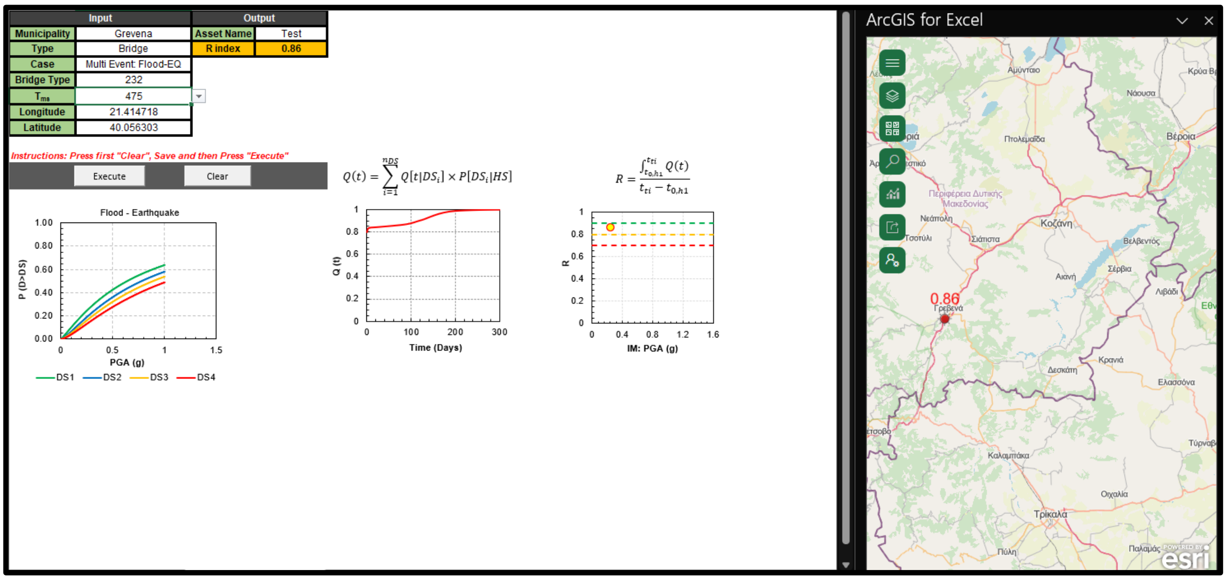
Instructions: Press first "Clear", Save and then Press "Execute"

$$Q(t) = \sum_{i=1}^{nDS} Q[t|DS_i] \times P[DS_i|HS]$$

$$R = \frac{\int_{t_{0,h1}}^{t_{ri}} Q(t)}{t_{ri} - t_{0,h1}}$$

Figure 18: Resilience analysis of Kalogirou bridge (bridge category #232) for a flood event with T_{mf}=100 years.

- **Multiple Events : Flood (FL), return period T_{ms}= 100 years, and subsequent Earthquake (EQ), return period T_{ms}= 475 years**



Input		Output	
Municipality	Grevena	Asset Name	Test
Type	Bridge	R index	0.86
Case	Multi Event: Flood-EQ		
Bridge Type	232		
T_{ms}	475		
Longitude	21.414718		
Latitude	40.056303		

Instructions: Press first "Clear", Save and then Press "Execute"

$$Q(t) = \sum_{i=1}^{n_{DS}} Q[t|DS_i] \times P[DS_i|HS]$$

$$R = \frac{\int_{t_{0,h1}}^{t_{ri}} Q(t)}{t_{ri} - t_{0,h1}}$$

Figure 19: Resilience analysis of Kalogirou bridge (bridge category #232) for a flood event with T_{mf}=100 years followed by an earthquake event with T_{ms}=475 years.

Table 6 summarizes the R index values of Kalogirou bridge computed for the examined hazard scenarios. For the examined hazard scenarios, the bridge reveals relatively high to high resilience.

Table 6. Summary of R index of Kalogirou bridge computed for examined hazard scenarios.

Hazard scenario	Hazard(s)*	Return periods (T_{mf}, T_{ms})	R index	Resilience Grade
Single	EQ	475	0.93	High
Single	FL	100	0.96	High
Multiple	FL/EQ	100/475	0.86	Relatively high

*EQ: earthquake event, FL: flood event

4.2 Application on Polymilos twin tunnels (S13 tunnels)

4.2.1 Tunnels description

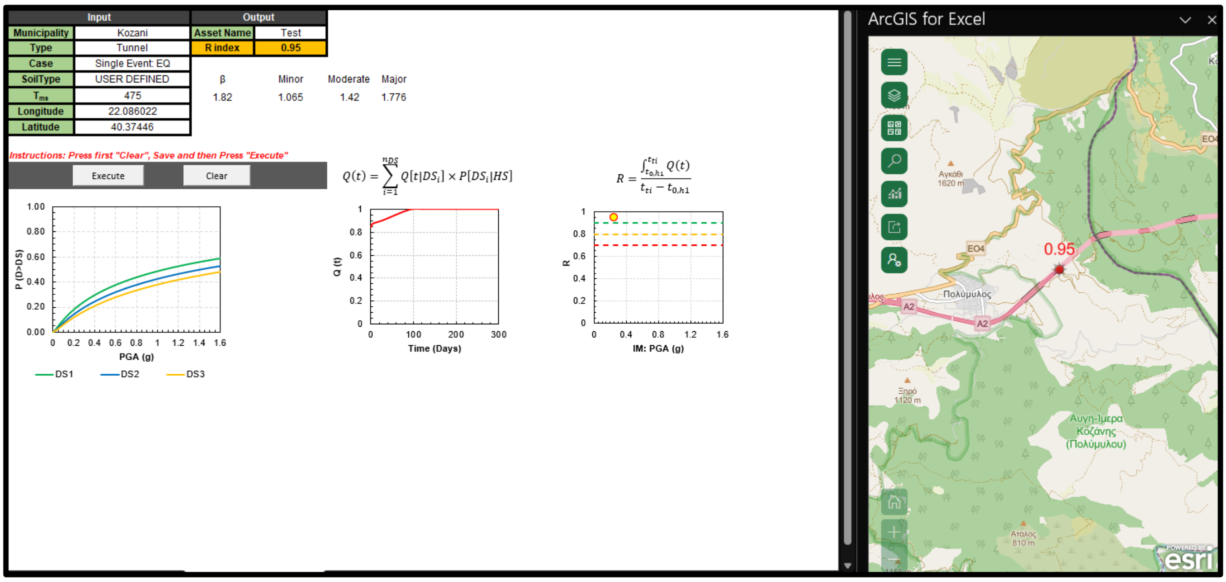
Polymilos twin tunnels (S13 tunnels) are selected as case study. The tunnels have lengths ranging between 797.5 m and 521.7 m (left and right tunnel). The analysis is conducted assuming a section of the tunnels embedded at a depth of 25 m (shallower sections are the crucial ones). INFRARES software is used to apply the methodology. The fragility curves proposed by Sarkar & Pareek (2021) for the assessment of tunnels against a single earthquake event are employed in the analysis.

Figure 20: Polymilos tunnels (S13 tunnels) of Egnatia Motorway.

4.2.2 Resilience assessment

The results from the INFRARES software application for selected single seismic hazard scenarios are provided in Figure 21 and Figure 22. Table 7 summarizes the R index values of Polymilos tunnels computed for the examined hazard scenarios. The tunnels exhibit a high resilience grade for all examined hazard scenarios.

- **Single Event : Earthquake (EQ) , return period T_{ms}= 475 years**



Input		Output	
Municipality	Kozani	Asset Name	Test
Type	Tunnel	R index	0.95
Case	Single Event: EQ		
SoilType	USER DEFINED		
T_{ms}	475		
Longitude	22.086022		
Latitude	40.37446		

β	Minor	Moderate	Major
1.82	1.065	1.42	1.776

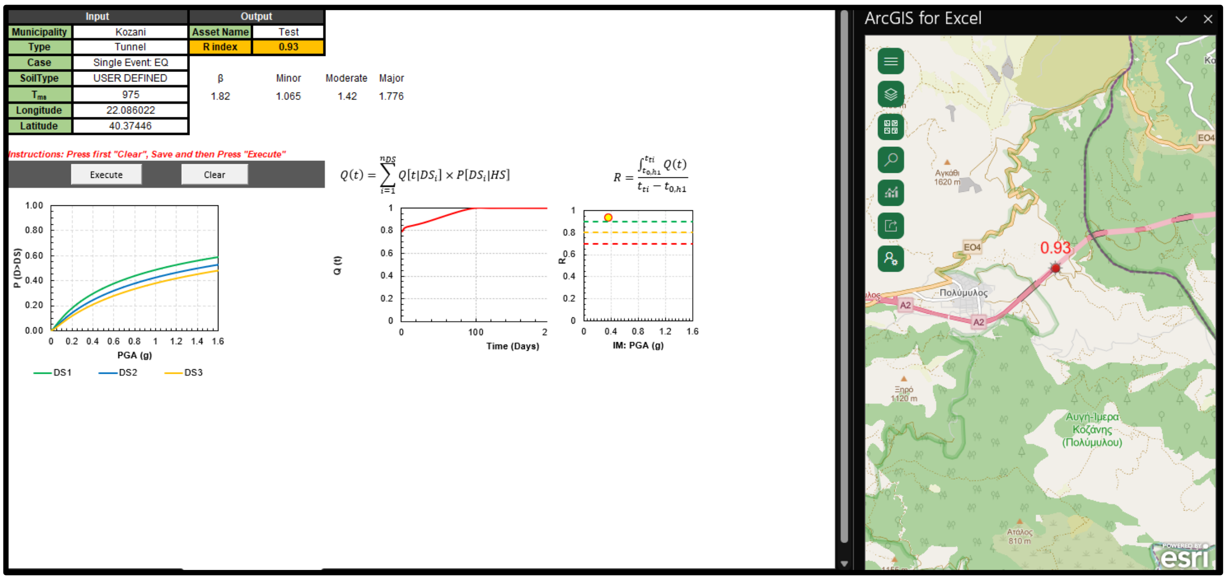
Instructions: Press first "Clear", Save and then Press "Execute"

$$Q(t) = \sum_{i=1}^{n_{DS}} Q[t|DS_i] \times P[DS_i|HS]$$

$$R = \frac{\int_{t_{0,h1}}^{t_{ti}} Q(t)}{t_{ti} - t_{0,h1}}$$

Figure 21: Resilience analysis of Polymilos tunnels for an earthquake event with T_{ms}=475 years.

- **Single Event : Earthquake (EQ) , return period T_{ms}= 975 years**



Input		Output	
Municipality	Kozani	Asset Name	Test
Type	Tunnel	R index	0.93
Case	Single Event: EQ		
SoilType	USER DEFINED		
T_{ms}	975		
Longitude	22.086022		
Latitude	40.37446		

β	Minor	Moderate	Major
1.82	1.065	1.42	1.776

Instructions: Press first "Clear", Save and then Press "Execute"

$$Q(t) = \sum_{i=1}^{n_{DS}} Q[t|DS_i] \times P[DS_i|HS]$$

$$R = \frac{\int_{t_{0,h1}}^{t_{ri}} Q(t)}{t_{ri} - t_{0,h1}}$$

Figure 22: Resilience analysis of Polymilos tunnels for an earthquake event with T_{ms}=975 years.

Table 7. Summary of R index of Polymilos tunnels computed for examined hazard scenarios.

Hazard scenario	Hazard(s)*	Return period (T_{ms})	R index	Resilience Grade
Single	EQ	475	0.95	High
Single	EQ	975	0.93	High

*EQ: earthquake event

5. Conclusions

The methodology for the resilience assessment of road bridges and tunnels under various single or multiple hazard scenarios, as well as *INFRARES software*, both developed within INFRARES project, are presented in the form of guidelines allowing for an easy use by the end-users (such as governmental/public authorities and operators, stakeholders). The report includes the principals and methods for the fragility and resilience assessment of bridges and tunnels of transportation infrastructures, as well as examples of applications from the selected case study in Egnatia Motorway in Western Macedonia, Greece.

References

Argyroudis, S.A., Mitoulis, S.A., Hofer, L., Zanini, M.A., Tubaldi, E., Frangopol, D.M. (2020) Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *Science of Total Environemnt*. 714:136854.

HAZUS (2020) Hazus Earthquake Model Technical Manual. Hazus 4.2 SP3. FEMA (https://www.fema.gov/flood maps/tools-resources/flood-map-products/hazus/user-technical-manuals).

Karatzetzou, A., Stefanidis, S., Stefanidou, S., Tsinidis, G., Pitilakis, D. (2022). Unified hazard models for risk assessment of transportation networks in a multi-hazard environment. *International Journal of Disaster Risk Reduction*, 75: 102960.

Markogiannaki, O., Karatzetzou, A., Stefanidou, S., Tsinidis, G. (2023) Resilience assessment of road bridges in multi-hazard environment. *9th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2023)*, 12-14 Jun 2023, Athens, Greece.

Sarkar, R., Pareek, K. (2021). Influence of stratification and assessment of fragility curves for mountain tunnels. *Geotechnical Engineering*, 174(3):279-290.

Tsinidis, G., Karatzetzou, A., Stefanidou, S. (2023) Probabilistic seismic demand models for the assessment of tunnels and underground structures. *9th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2023)*, 12-14 Jun 2023, Athens, Greece.