Project[1] Number: [746298]
Project Acronym: [TRANSRISK]
Project title: [Vulnerability and risk assessment of transportation systems of assets (SoA) exposed to geo-hazards]

Periodic Technical Report
Part B

Period covered by the report: from [01/09/2017] to [01/03/2020]
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[1] The term 'project' used in this template equates to an 'action' in certain other Horizon 2020 documentation

1. Explanation of the work carried out by the beneficiaries

Overview

The diverse yet complementary expertise of the Fellow (**Dr S Argyroudis**), the Supervisor (Dr S Mitoulis), the Host Organisation (University of Surrey), and the Partner Organisations (Transport Research Laboratory, TRL and the Norwegian Geotechnical Institute, NGI) were combined in a niche area of interest on the **resilience of transport infrastructure** In this respect, **TRANSRISK** project integrated research and knowledge from different disciplines, i.e. infrastructure engineering, numerical modelling and computational mechanics, geotechnical engineering, geo-hazards, risk analysis and management aspects. This multi-sectoral nature of the project also included interaction with transportation authorities, stakeholders and industrialists, e.g. ARUP, Highways England, Network Rail, JBA Trust, to produce meaningful and practical research results. The Supervisors from Partner Organisations, Prof MG Winter (TRL) and Prof AM Kaynia (NGI) provided training and support to the Fellow during the research project. The dissemination and outreach activities provided the Fellow with the ability to communicate with researchers, practitioners, industrialists and stakeholders from different fields and with diverse audiences and opened-up new opportunities and collaborations with the academia and the industry.

This research contributed to the enhancement of current practices by moving toward the multi-hazard lifetime resilience assessment of infrastructure and provided useful insights for the resilience-based design and management of infrastructure throughout their lifetime, leading to cost savings and improved services. In particular, the **contribution beyond the state of the art** is summarised in the following:

- A new concept for transport infrastructure systems of assets (SoA) in ecosystems exposed to geotechnical and climatic hazards was introduced.
- A novel methodology for the development of numerical fragility functions for transport SoA exposed to multiple hazards was proposed.
- New fragility curves/surfaces for transport SoA exposed to multiple hazards were developed based on advanced numerical models.
- Damage modes for flood critical bridges were defined and new restoration models were developed based on an expert elicitation approach.
- A new classification of multiple hazard sequences considering their nature and impacts was proposed.
- A novel framework for the quantitative resilience assessment of critical infrastructure, subjected to multiple hazards including their temporal variability was proposed, with resilience indices considering direct and indirect losses.
- The above were applied to well-selected case studies, aiming to provide to network owners and operators with robust decision-making and prioritisation processes for building resilience into their infrastructure.
- The use of monitoring systems and digital innovation from emerging technologies was also explored, for enhancing the accuracy, reliability and rapidity of exposure data, hazard measures, fragility, restoration and functionality models and risk management.

Overall, research progressed as planned, and objectives were achieved and exploited beyond the duration of the project, while **publicity, visibility** and **outreach** were maximised through the following actions:

- Publications in high-impact scientific journals (2 published, another 10 under review and/or preparation), and international conferences (8 papers published), a total of 20 publications
- Participation in grant bidding (9) and successful research and consulting projects (5 successful, for 2 decision is pending)
- Participation in conferences and other events (10)
- Seminars and training courses (6)
- Organisation of special sessions in international conferences (4)
- A new and highly visited website was developed (www.infrastructuResilience.com)

- Periodical posts in social media (ResearchGate, Linkedin, Facebook)
- Part of the research was presented in taught modules at the University of Surrey (5 lectures).

1.1 Objectives

The main aim of the **TRANSRISK** project against the current state-of-the-art was to develop adaptable fragility and resilience models for **critical transport Systems of Assets (SoA)** exposed to multiple hazard effects. The specific measurable objectives of the **TRANSRISK** project are (*as described in section 1.2 of the DoA*):

Obj 1. *To create a set of advanced numerical models of representative transportation SoA subjected to critical combinations of geo- and climatic hazards with focus on the resulting geotechnical effects (i.e., flooding/scouring, ground movements, dynamic loads); the SoA models will be validated against models available in the literature and also on the basis of well-documented case studies from recent failures.*

Summary of the work carried out towards the achievement of Obj 1: Advanced numerical models (2D and 3D) were generated using state-of-the-art methods and tools for the detailed numerical modelling of critical and representative SoA, i.e. (i) a highway/railway embankment/slopes with foundation soil (SoA1), (ii) a bridge with its components (deck, abutment, piers and foundations), backfills and foundation soil (SoA2). Both examined SoA were exposed to individual and combined hazards, e.g. flood, scour and/or seismic shaking effects. These models included detailed simulation of materials, geometries, structural variations, non-linearities, soil structure interaction and combined hazard effects and have been validated on the basis of closed-formed solutions, models built with different software tools and evidence from previous failures. The numerical models have been used for the development of fragility models (Obj 2).

Obj 2. *To develop and verify a set of fragility models for assessing the vulnerability of specific transportation infrastructure SoA subjected to critical combinations of geo- and climatic hazards. These will be the reference fragility models representing the as-designed and as-built SoA. These models will then be extended to adaptable fragility models that will account for: (a) the deterioration of assets depending upon the age of the asset and previous hazard effects, and (b) improvements of the assets on the basis of realistic retrofitting/strengthening methods.*

Summary of the work carried out towards the achievement of Obj 2: A novel methodology was proposed for the development of fragility models for transport SoA subjected to multiple hazards (Argyroudis et al. 2019a). This methodology was applied to develop new multiple hazard fragility models for the representative SoA and their numerical models as defined in Obj 1. This was achieved on the basis of parametric analyses, to account for uncertainties in: (i) the characteristics of multiple hazard actions, i.e. water level, scour hole formation, forces due to water flow and accumulation of debris acting on bridge piers, seismic loading, (ii) the material properties, i.e. sand/clay, saturated/dry, (iii) the geometry and structural types of the SoA, e.g. width/height of embankment, type of deck to piers/abutments connection (integral or through bearings). Evolution of models due to deterioration and/or accumulation of natural hazard stressors on the asset throughout their lifetime was also considered. Improvement on the basis of structural enhancements and/or partial or full restoration after the occurrence of damage due to a precedent hazard effects were accounted in the models.

Obj 3*. To apply the adaptable fragility models to a part of a real transportation network within Europe. This will help toward estimating the risk and the associated losses due to recorded hazards for different return periods, as a means to enable the unbiased allocation of resources in decision-making and disaster management.*

Summary of the work carried out towards the achievement of Obj 3: This objective was extended to include quantification of resilience for transport infrastructure exposed to multiple hazards. In this respect, a classification of multiple hazard sequences considering their nature and impacts was proposed.

Subsequently, a novel framework for the quantitative resilience assessment of critical infrastructure, subjected to multiple hazards was proposed (Argyroudis et al. 2020a), considering the vulnerability of the assets to hazard actions, and the rapidity of the recovery after the occurrence of induced consequences and structural damages, including the temporal variability of the hazards. New restoration models have been proposed for damaged bridges under scour and earthquake hazards using expert elicitation approaches. This also put forward well-informed asset resilience indices, which account for the full, partial or no restoration of asset damage between the subsequent hazard occurrences as well as the direct (repair cost) and indirect (due to traffic detour) losses. The proposed framework was applied (i) on a typical highway bridge, which is exposed to multiple hazard scenarios (flood events followed by earthquakes), considering temporal variation of hazards occurrences and pragmatic restoration strategies, (ii) on a portfolio of bridges as part of a real transport network in Thessaloniki, Greece for different earthquake scenarios, (iii) the Queensferry Crossing bridge in Scotland, exposed to accumulation of ice bridge. This research contributes to the enhancement of current practices for resilience-based management of infrastructure assets, leading to cost savings and improved services.

1.2 Explanation of the work carried per WP

1.2.1 Work Package 1: Documentation of selected case studies

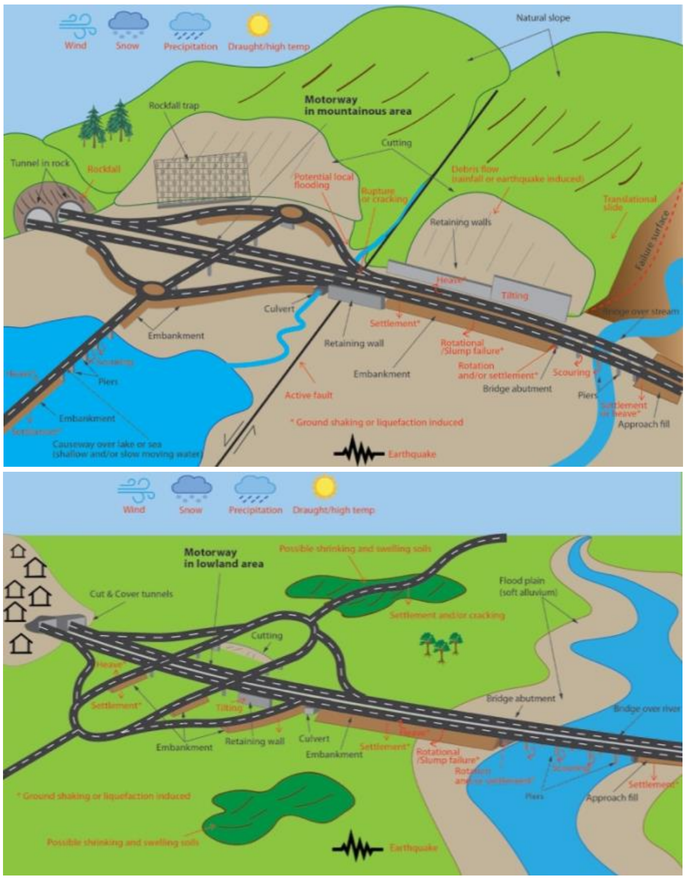
Task 1.1 Selection of critical scenarios. An overview and collection of information concerning critical hazard effects on railway/highway infrastructure System of Assets (SoA) was carried out. The effects of critical hydraulic and geotechnical hazards on road infrastructure, and relevant mitigation measures were summarised, including common damage modes (Argyroudis et al. 2019a). Critical SoA and hazard attributes have been defined based on well-documented recent damages. The effects of the following **hazards** were reviewed: fluvial/river flood due to extreme precipitation (including overbank and flash flooding); pluvial/surface flood due to extreme precipitation; underground water; sea level rise and storms (flood surge); landslides (rainfall or earthquake-induced, including sliding, debris flow, mudflow); drought; extreme hot weather; wildfires; snow; cold & freeze; strong winds; earthquakes (ground shaking, ground failure due to liquefaction or fault rupture); any hazard that leads to impacts due to geographic interdependencies (mainly in urban environments). The following **transport assets** were included in the review: tunnels; bridges; retaining walls; embankments and cuttings; roads; pavements; signalling and ITS. Common typologies of transport assets met in Europe were also defined (Table 1).

Table 1. Main parameters of road assets' typology (Argyroudis et al. 2019a).

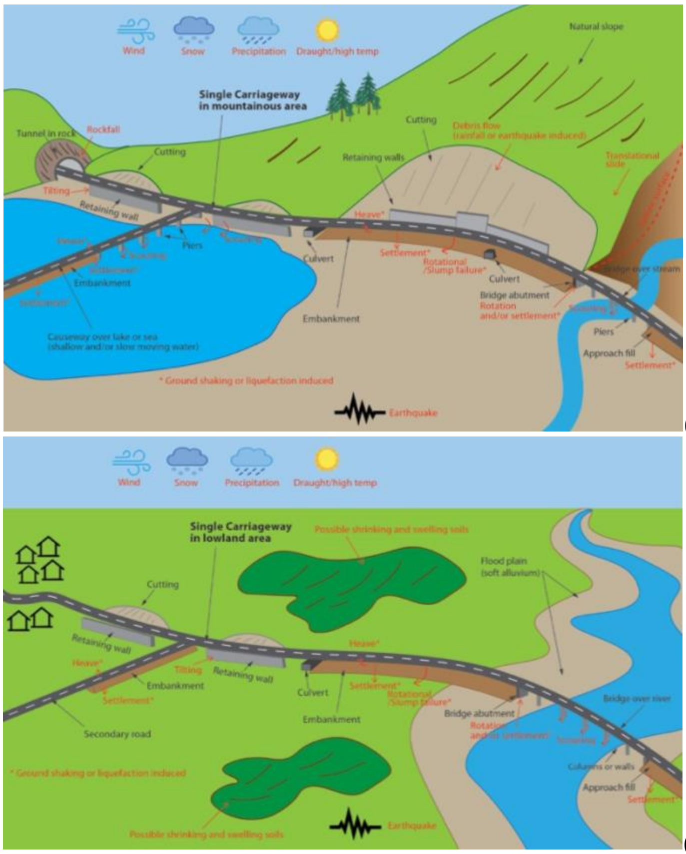
Asset	Typology
High capacity and speed roads (e.g. Controlled access motorways)	Horizontal alignment: variable, mainly depends on the design speed Vertical alignment: 3% (desirable max grade) Standard lane width: 3.65m Standard hard shoulder width: 3.65m Standard median strip width: 1.0m Standard total width per direction (incl. shoulders and median strip): 11.95m for 2 lanes, 15.6m for 3 lanes, 19.3m for 4 lanes. Speed limit: 110-120 kmph
Lower capacity and speed roads (e.g. Single carriageways)	Horizontal alignment: variable, mainly depends on the design speed Vertical alignment: 6% (desirable max grade; in hilly terrain steeper gradients may are present) Standard lane width: 3.65m Standard hard strip width: 1.0m Standard total width (including strips): 9.3m (new design), as low as 6.8m (for old design) Speed limit: <=90 kmph
Embankment /Slope/Cutting	Variable height, depending on local geomorphology; Typical height classification: 0-2.5m, 2.5-5.0m, >5.0m

	Typical slope angle: 1.5(H):1(V) - 2(H):1(V), in some cases 2.5(H):1(V) - 3(H):1(V) depending on the material and design specifications Drainage type: None, French drain, Open ditch
Bridge	Commonly based on the number of spans and length, particular design considerations, material, type of pier and abutment and deck continuity. Geometry is variable depending on bridge type and local geomorphology. Typical pier height: 5.0 to 20.0 m. Typical deck cross section height: 1.0 to 2.0 m. Typical span length: 15.0 m to 35.0 m.
Bridge abutment	Based on the structural type of the bridge (e.g. stub, partial or full depth, integral abutment). Other features: depth and soil conditions of the foundation Geometry is variable depending on bridge type and local geomorphology. Typical abutment height: 2.0 to 10.0 m.
Tunnel	Commonly based on construction method (bored or mined, cut-and-cover, immersed), cross-section shape (circular, rectangular, horseshoe, etc.), depth (surface, shallow, deep), geological conditions (rock, alluvial), supporting system (concrete, masonry, steel, etc.)
Retaining wall	Common rigid types: gravity, cantilevered, sheet piling, bored pile, anchored, Flexible types: reinforced soil Variable height depending on retained soil mass, commonly 3.0 to 15.0 m.
Backfill (bridge abutment, retaining wall)/ Embankment/Slope/Cutting	Soil material, ground angle, and water content are of main interest

Based on the literature review conducted it was realised that the available vulnerability and risk assessment frameworks typically consider individual assets of the transport infrastructure, exposed to one hazard, and they are static in the sense that they neglect changes of the asset performance during its life. Additionally, in most cases, the available models are simplified, and they focus on bridges. Moreover, they usually ignore the geomorphological and topographical conditions of the surrounding environment as well as the classification of the assets in terms of road capacity or speed limits. Nevertheless, infrastructure comprises Systems of Assets (SoA), i.e. a combination of interdependent assets exposed to multiple hazards, depending on the environment within which these reside, whilst their performance changes due to deterioration or improvements that take place during their life. In addition, the SoA performance depends on the classification and typology characteristics of the infrastructure. In this respect, a new concept of the transport infrastructure SoA in ecosystems was introduced (Figure 1 and Figure 2), referring to inter-urban roads and illustrating he different elements that comprise the system and the geotechnical and climatic hazards to which the system is subjected. The infrastructure is classified based on: (i) the road capacity and speed limits, i.e. high capacity and speed roads, such as interstate highways, motorways and dual-carriageways, and lower capacity and speed roads, such as single carriageways, and, (ii) the geomorphological and topographical conditions, i.e. mountainous or lowland areas.



(a)
(b)
Figure 1. Transport infrastructure in diverse ecosystems exposed to multiple hazards: High capacity and speed roads (e.g. motorways) in (a) mountainous areas, (b) lowland areas (Argyroudis et al. 2019a).



(a)
(b)
Figure 2. Transport infrastructure in diverse ecosystems exposed to multiple hazards: Lower capacity and speed roads (e.g. single carriageways) in (a) mountainous areas, (b) lowland areas (Argyroudis et al. 2019a).

Task 1.2 Definition of benchmark case studies of SoA exposed to hazards. A feasible number of case studies was selected for modelling and validation purposes within WP2, against antecedent geo- and climatic events and the generation of fragility models in WP3: **SoA1: slopes responding interacting with a road pavement or railway tracks on embankments and supported by retaining structures** (Figure 3a), exposed to landslides, potentially triggered by precipitation or earthquakes (ground shaking or/and liquefaction), flooding effects or/and ground shaking. Rotational or slump failure of embankments may occur due to the same hazards. Degradation of the SoA, in this case, may be the result of embankment erosion or foundation scour over flooded sea, lakes or rivers and potential residual dislocations of the retaining structures. The stability of the SoA may deteriorate during its lifetime as a result of an increase in the stresses or traffic loads, decrease of soil shear strength due to changes in pore water pressure and presence of organic materials. Potential improvement measures include shotcreting, soil anchors, nailing, vegetation, and improved drainage. **SoA2: bridge, abutment, foundations, backfill** (Figure 3b). The multiple hazard scenarios may include settlements, heave or/and local sliding of the embankment and approach fill due to ground shaking or liquefaction among other hazards. Bridge components such as the deck, abutment, piers and foundations, may suffer damage due to seismic shaking, settlements, scouring and liquefaction. Degradation, in this case, may occur due to corrosion of the reinforced or prestressed concrete elements, scouring of the foundation soil and residual dislocations of the abutments. Similarly, degradations of the approach fill can be due to traffic loads and residual deflection of the backfill, such as settlement or heave. Improvements include strengthening of the piers and/or the abutments, improvement of the compacted state of the backfill or some means of reinforcement.

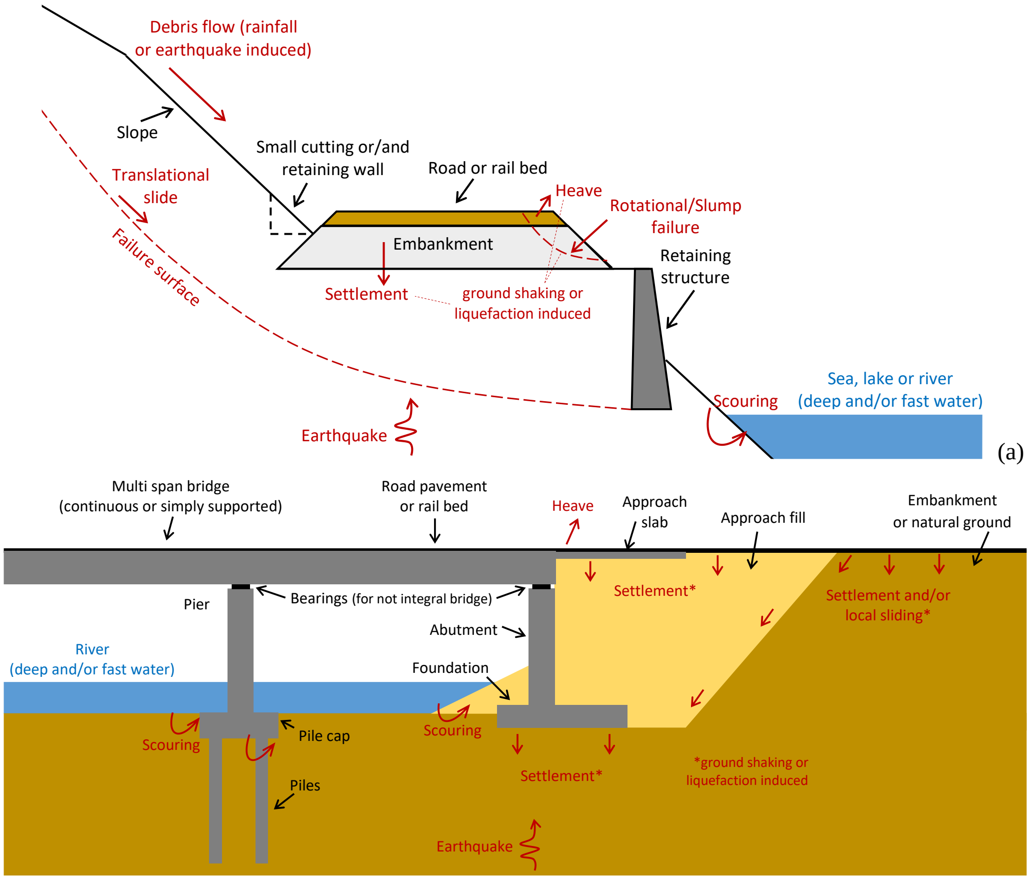


Figure 3. Multiple hazard effects on representative transport System of Assets: (a) embankment, slope, retaining structure (SoA1), (b) bridge, abutment, foundations, backfill (SoA2) (Argyroudis et al. 2019a).

Task 1.1 and task 1.2 were performed in collaboration with Prof M.G. Winter, during the secondment of Dr S. Argyroudis in TRL (Transport Research Laboratory).

1.2.2 Work package 2: Generation and validation of advanced numerical models for SoA

Task 2.1 Advanced numerical simulations. State-of-the-art methods and tools for the detailed numerical modelling of SoA were evaluated. Initially, simple models that provided a fundamental understanding of the SoA response to hazards were employed. Subsequently, advanced numerical models were generated for each critical SoA, modelling in detail the materials, geometries, structural variations, non-linearities, soil structure interaction effects etc. The capacity of the Host Organisation was fully utilized taking advantage of the expertise and the available advanced software platforms to achieve the aforementioned simulations. In particular PLAXIS 2D, PLAXIS 3D and SAP2000 software were utilised. Representative examples of numerical models are shown in Figure 4 and Figure 5 for SoA1 and Figure 6 and Figure 7 for SoA2.

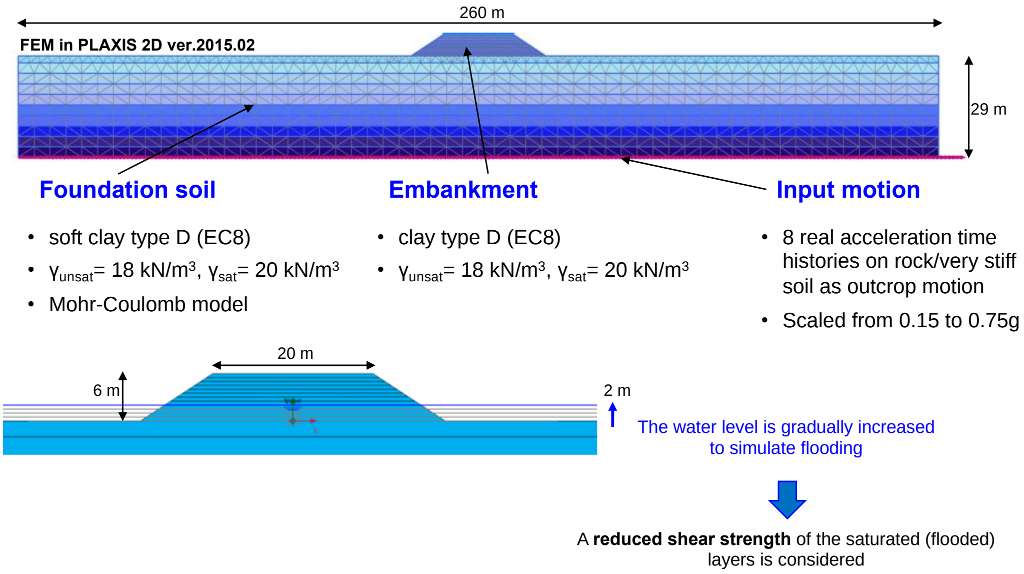


Figure 4. Numerical model in Plaxis 2D for SoA1: roadway/railway embankment and foundation soil, subjected to flood and seismic excitation

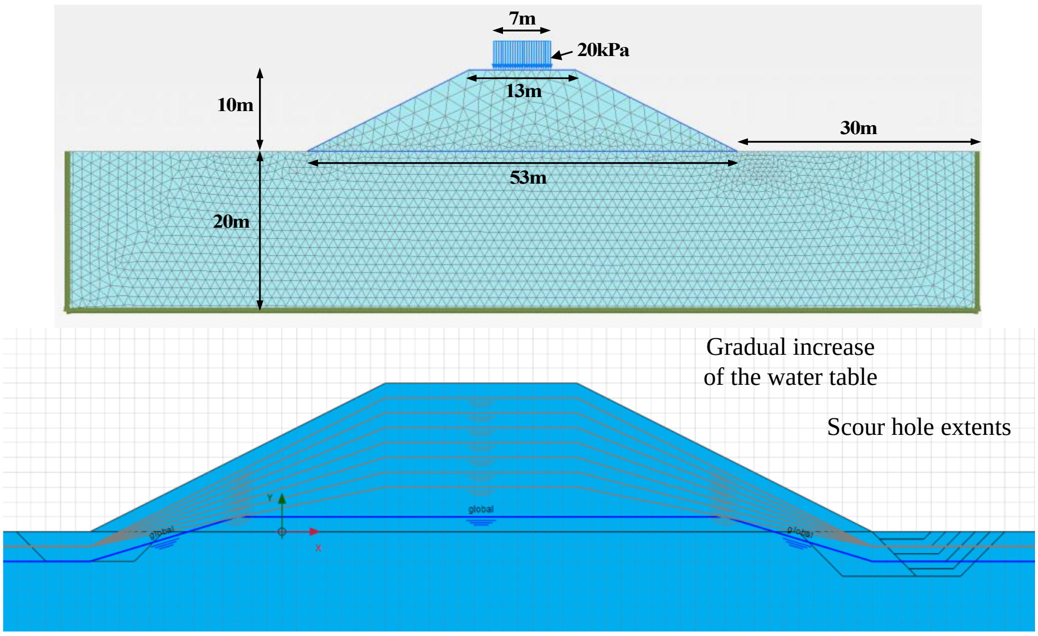


Figure 5. Numerical model in Plaxis 2D for SoA1: embankment and foundation soil, subjected to moisture ingress and scour effects

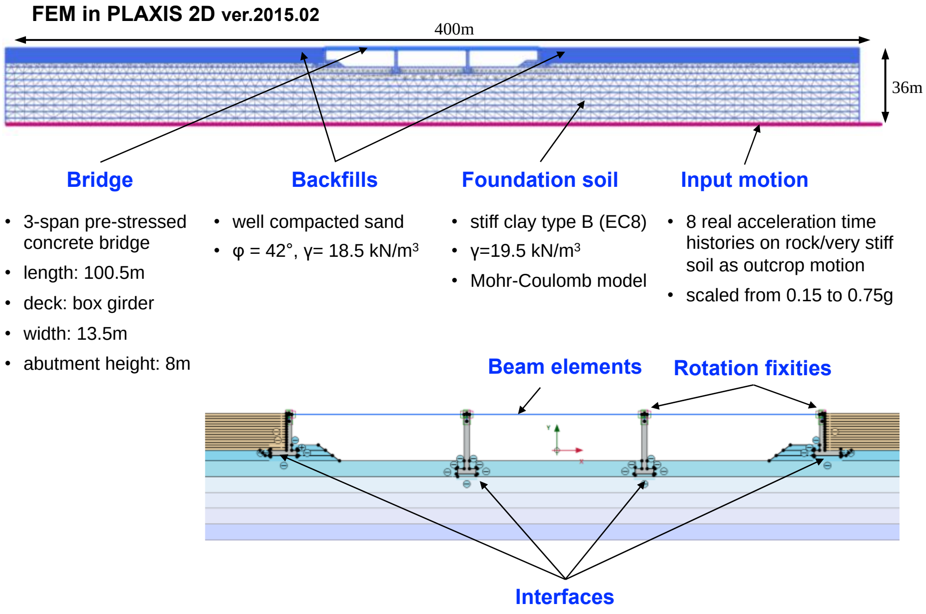


Figure 6. Numerical model in Plaxis 2D for SoA2: bridge, backfills, foundation soil subjected to seismic shaking

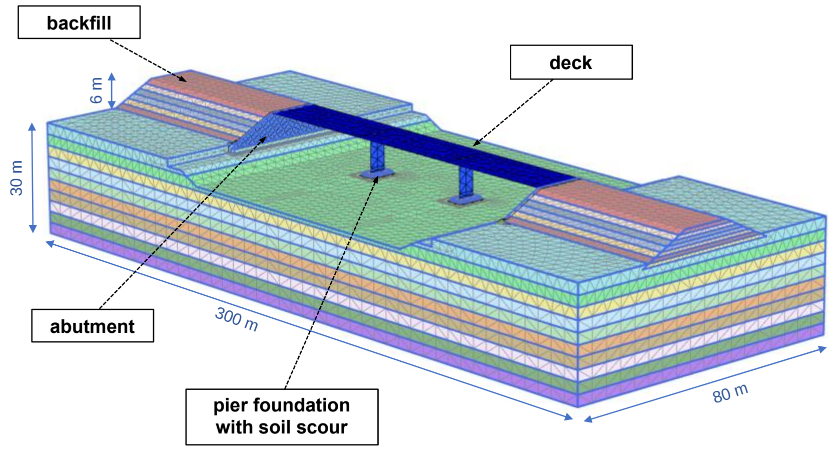


Figure 7. Numerical model in Plaxis 3D for SoA2: bridge, backfills, foundation soil, subjected to flood and scour effects

Task 2.2 Validation and calibration of the numerical models of SoA. The selected case studies of Task 1.2 were analysed, and results were compared against ad-hoc approaches (closed-form solutions), frequently adopted in the literature as well as previous studies (e.g. Argyroudis and Kaynia 2015 for SoA1, Tsinidis et al. 2019 for SoA2). Validation also included the comparison of the results using different software platforms. For example, the response of integral bridges in Plaxis software was compared with models developed in SAP2000 software and with closed-form solutions for reinforced concrete frameworks or beams. The calibration of the numerical models included the setup of boundary conditions, interfaces, simulation of hazard effects, i.e. water level, scour hole formation, seismic input motion. Modelling challenges in Task 2.1 and Task 2.2 have been tackled in collaboration with Prof A.M. Kaynia in NGI (Norwegian Geotechnical Institute). For example, these included the definition of boundary conditions of dynamic analysis in Plaxis software, the selection of properties for the saturated and scoured soil material (e.g. strength, damping, stiffness), and meshing issues and errors during the simulations of scour hole geometries around the bridge foundations.

1.2.3 Work package 3: Generation of adaptable fragility functions for benchmark SoA exposed to geo- and climatic hazards

Task 3.1 Reference fragility functions. A novel methodology was proposed for the development of fragility functions for transport SoA subjected to geo- and climatic multiple hazards (Figure 8). This methodology was applied to develop new multiple hazard fragility models for the representative SoA of WP1 using the numerical models of WP2. The key steps for the derivation of new analytical fragility functions for the benchmark SoA included the following: (i) Definition of the basic configurations of the SoA, including geometry and material of the assets and the components and properties of the soil. For SoA1, i.e. embankment and foundation soil, different geometries and soil conditions were selected, while for SoA2, i.e. bridge, backfills and foundation soil, different bridge types, e.g. isolated through bearings or integral structures, and different soil conditions were examined. The uncertainty in capacity, β_C, was quantified on the basis of an expert judgement approach. (ii) Selection of engineering demand parameters (EDPs) for each asset or component and relevant limit states and thresholds for the definition of damage states. For SoA1, damage states were defined based on the settlements on the top of the embankment, while for SoA2, EDPs included the bending moment of the deck, pier and abutments, the settlement of the foundation and the displacement of the bearings. Relevant thresholds for the definition of damage states (e.g. minor, moderate, extensive, complete) were defined based on the literature and/or by applying expert judgment. These damage states were correlated to restoration works, downtimes and loss of functionality (see WP4 in section 1.2.4). The uncertainty in limit states, β_{LS}, was estimated on the basis of expert judgment. (iii) Definition of hazard actions and intensity measures. Sufficient, efficient and practical intensity measures were selected for each hazard, such as peak ground acceleration for earthquakes and flow depth, scour depth or water discharge in case of flash floods. For flood hazard, different flow depths and scour hole geometries were considered, and the effect of debris accumulation in the scour depth was also included in the analyses. For seismic hazard, a suite of strong ground motions was selected, to account for the uncertainties in hazard effects. Combinations of hazards were defined, such as flood followed by scour effects and earthquake excitations of different intensities. These combinations were extended in Task 3.2. (iv) 2D and 3D numerical models were employed to analyse the response of the SoA defined in step (i) subjected to different hazards or combination of hazard actions of a given sequence defined in step (iii). A feasible number of parametric numerical analyses of the calibrated models of WP2 were conducted to cover a sufficient range of SoA typologies and hazard effects. The results of the numerical analyses provided the required EDP for each component or/and asset for the fragility analysis described in the following steps. (v) Evolution of damage and uncertainty in demand (β_D). The results of the analyses conducted in step (iv) in terms of EDPs are plotted versus the selected IM (e.g. PGA or peak flow discharge) for each asset or component representing the evolution of damage with increasing hazard intensity, usually on a logarithmic scale. A regression model that describes the correlation between the IM and EDP was then used. The uncertainty in demand, β_D, was calculated based on the dispersion of the logarithms of IM-EDP simulated data with respect to the regression fit. (vi) Generation of component, asset and SoA fragility curves/surfaces for single and multiple hazards correspondingly. Each fragility function requires the definition of two parameters (Eq. 1): IM_{mi}, that is the median threshold value of IM required to cause the i^{th} limit state) and β_{tot}, which is the total lognormal standard deviation. The total uncertainty was calculated at asset level assuming that the uncertainties in demand (β_D) as calculated in step (v), capacity (β_C) as per step (i) and definition of limit states (β_{LS}) as per step (ii), are statistically independent (see Eq. 2). The median value of IM_{mi} is obtained using the regression model defined in step (v) and the definitions of damage states for each component/asset defined in step (ii).
Results of this task have been presented in conference papers (Argyroudis et al. 2018a, 2018b, 2019b, Yuan et al. 2019) and further discussed in Task 3.2 below.

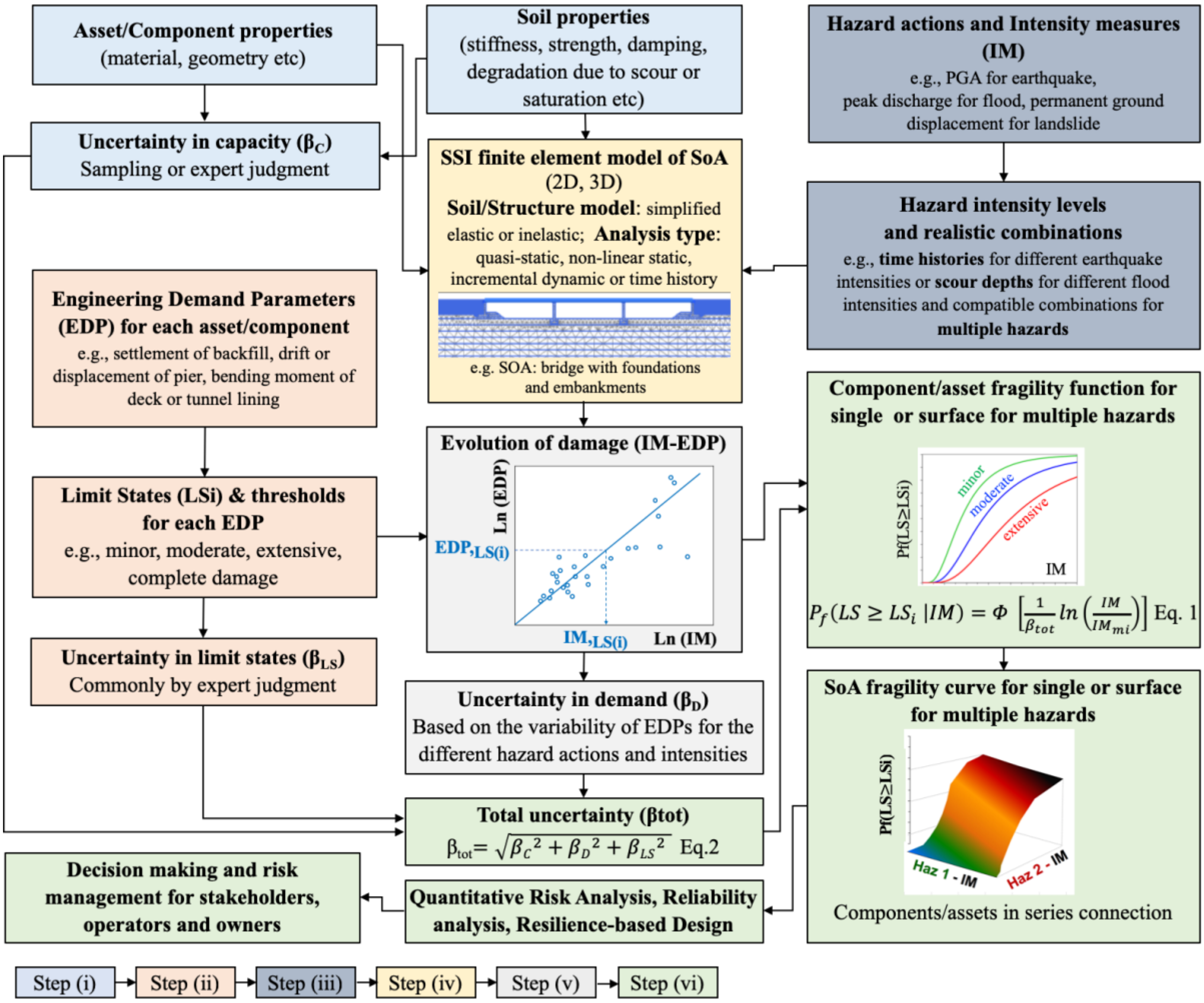
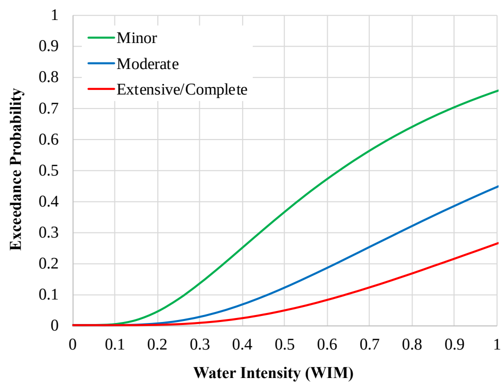


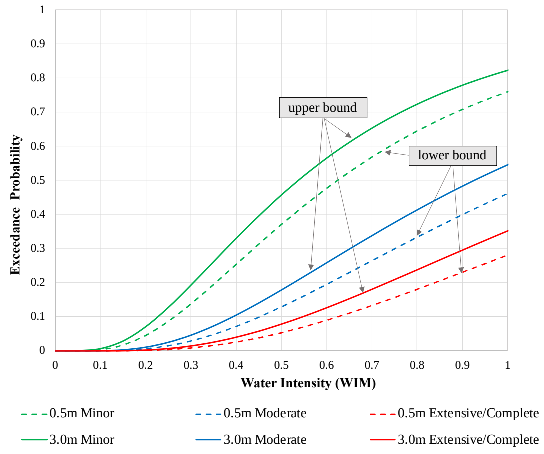
Figure 8. Flowchart for multiple hazard fragility functions of transport systems of assets (Argyroudis et al. 2019a).

Task 3.2 Adaptable fragility models. Fragility functions accounting for typical deterioration scenarios, combinations of hazards and improvement of SoA were generated following the steps described in Task 3.1. In particular, the following scenarios of **deterioration and damage accumulation** were examined:
SoA1: (i) Flooding at different heights, (ii) combinations of flooding, followed by scour effects at the toe of the embankment, (iii) flooding at different heights followed by variable seismic excitations.
SoA2: Global flooding, followed by gradually increased scouring effects: (i) only at one pier, (ii) only at one abutment, (iii) combinations of scour at the pier(s) and abutment(s) foundation, (iv) increase of scour depth and hydraulic forces due to the accumulation of debris at the pier, (v) seismic excitations following the scour effects (i to iii).
The study of potential **improvements** was mainly focused on SoA2, were the following mitigation measures were analysed:
(a) use of bearings as an isolation method, (b) increase of the geometry, and therefore the stiffness of the piers exposed to scour and seismic effects, (c) different soil conditions under the bridge foundations, i.e. sand or clay soil material, to investigate possible mitigation of the hazard effects.
In this task, collaboration with Prof. A.M. Kaynia (NGI) enabled modelling of advanced constitutive laws of materials. Preliminary results of this task were presented in the papers of Task 3.1. Another one publication is under review (McKeena et el. 2020), and another two journal publications are under preparation (Argyroudis et al. 2020, Stefanidou et al. 2020) including the development of adaptive fragility models for SoA2. Representative examples of fragility models are given in Figure 9 for SoA1 and Figure 10 and Figure 11 for SoA2.



$$\text{WIM} = \frac{h_{emb} - h_w}{h_{emb}}$$, WIM is the Water Intensity Measure, h_{emb} is the height of embankment, h_w is the depth to the groundwater table

(a)



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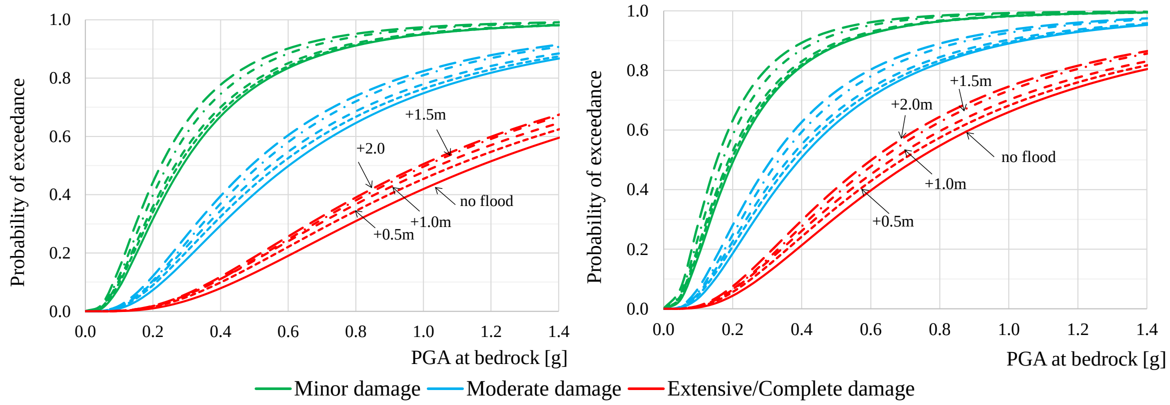
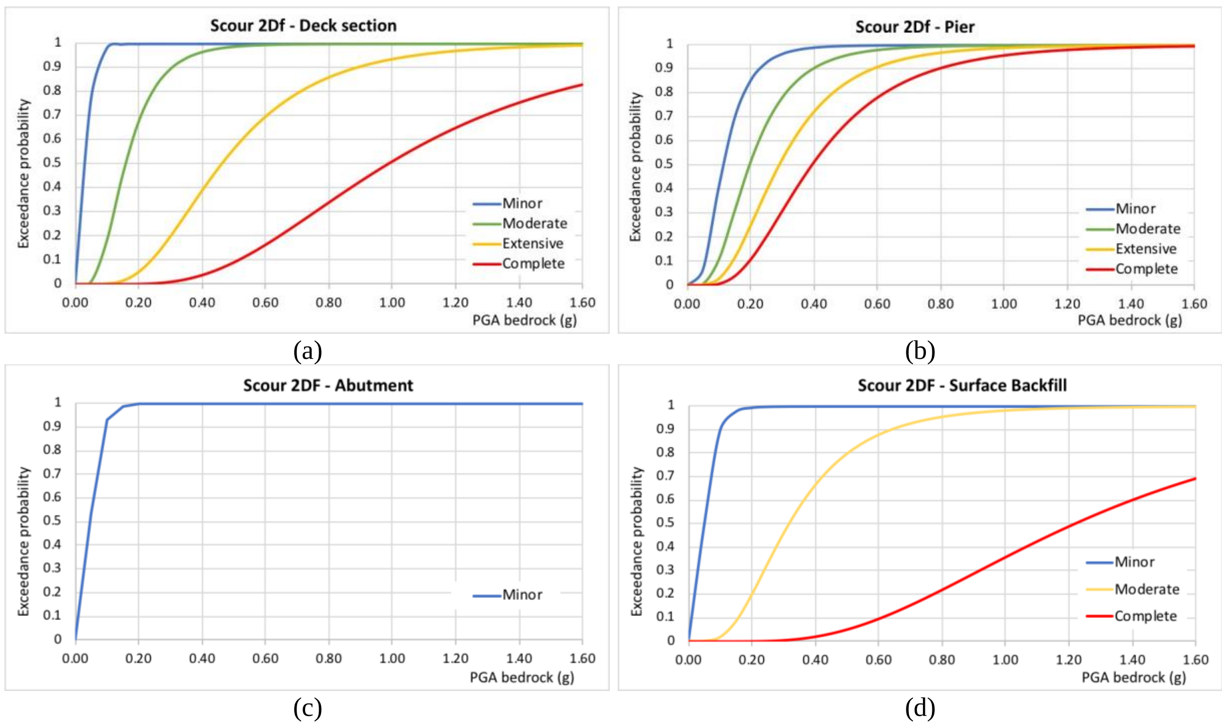
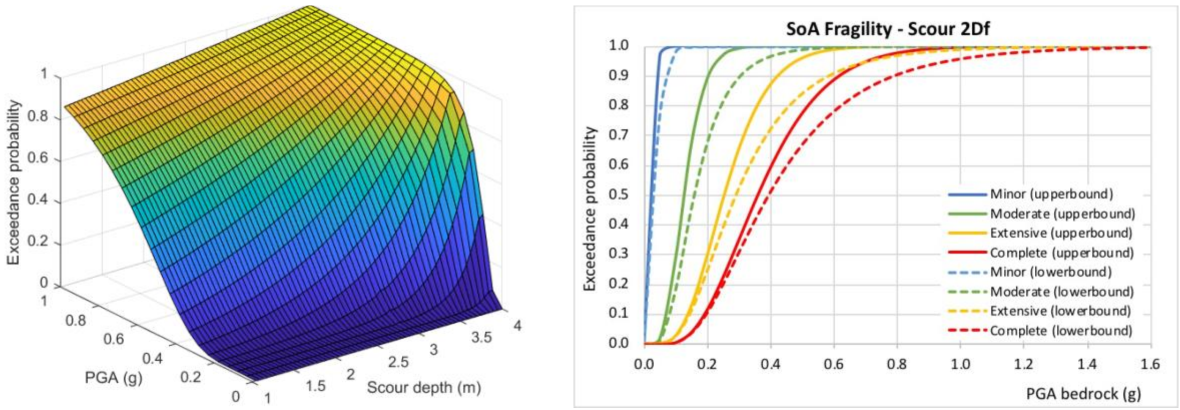


(c)

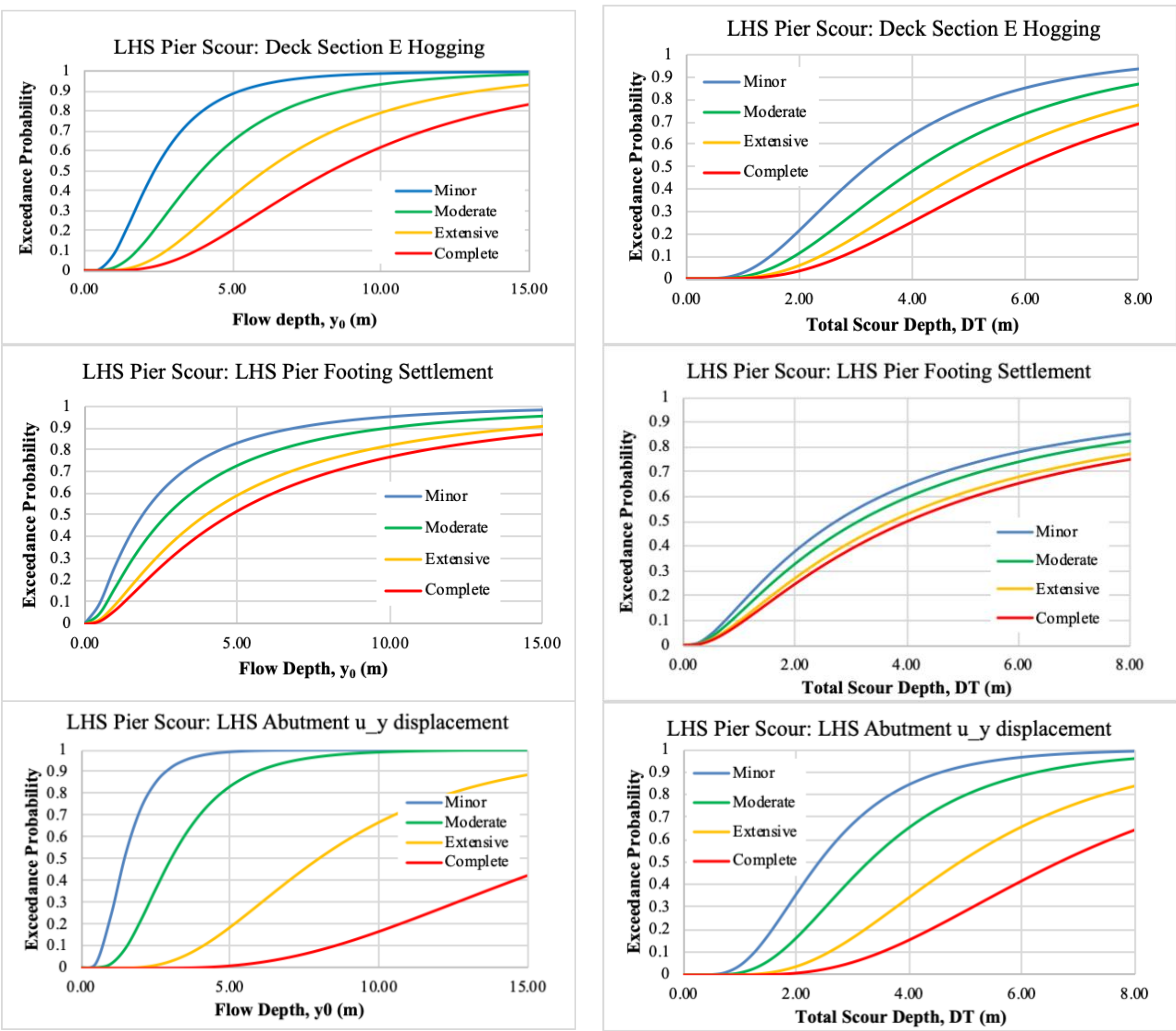
Figure 9. Examples of multiple hazard fragility functions for representative SoA1 (embankments) exposed to: (a) moisture ingress, (b) moisture ingress followed by scour at the toe overlain from 0.5m to 3.0m depth, (c) combination of flooding effects (inundation equal to 0.5, 1.0, 1.5 and 2.0 m from the embankment toe) followed by seismic excitations, for highways (left) and railways (right).

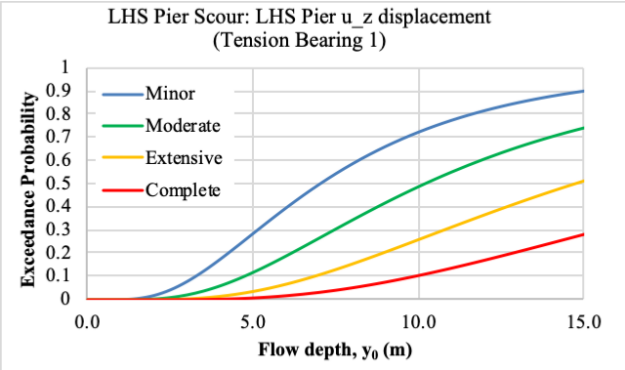




(e) (f)

Figure 10. Example of multiple hazard fragility functions for representative SoA2 (integral bridge, backfills and foundation soil) exposed to combined scour and seismic effects: (a) deck, (b) pier, (c) abutment, (d) backfill, (e) fragility surface for minor damage of the bridge pier, (f) SoA, for scour equal to two foundation depths (2Df) and earthquake excitations.





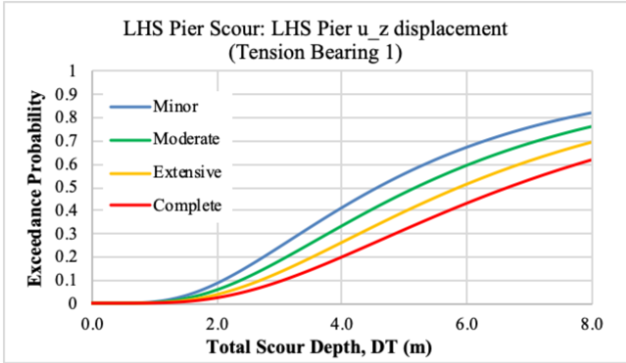


Figure 11. Examples of multiple hazard fragility functions for representative components of SoA2 (deck section, pier footing, abutment, bearings) exposed to flood, scour and debris accumulation effects, as a function of scour depth (right) and flow depth (left).

1.2.4 Work package 4: Application of fragility functions to a network scale

This work package was extended to include the development of a **novel resilience assessment framework** for transport infrastructure exposed to individual and multiple hazards and its application to parts of transport networks. This development was decided after understanding that no integrated framework that accounts for the nature and sequence of multiple hazards and their impacts, the different strategies of restoration, and hence the quantification of resilience in that respect exists. In this respect, this WP provided for the first time in the literature, a classification of multiple hazard sequences considering their nature and impacts. Subsequently, a novel framework for the quantitative resilience assessment of critical infrastructure, subjected to multiple hazards was proposed, considering the vulnerability of the assets to hazard actions, and the rapidity of the damage recovery, including the temporal variability of the hazards (Figure 12). The framework accounts for (i) the robustness of the assets to hazard actions, based on realistic fragility functions for individual and multiple hazards (as per WP3), and (ii) the rapidity of the recovery, based on realistic reinstatement and restoration models after individual and multiple hazard events. The framework allows quantifying the impact on the resilience of alternative restoration strategies following the occurrence of a hazardous event, including the cases of full, partial and even no restoration. A generalized index was defined to quantify the resilience in a unified way for different hazard and recovery scenarios. This index can be used to facilitate decision-making and prioritisation processes by infrastructure owners and operators by maximising the resilience of critical infrastructure based on efficient risk mitigation and restoration strategies.

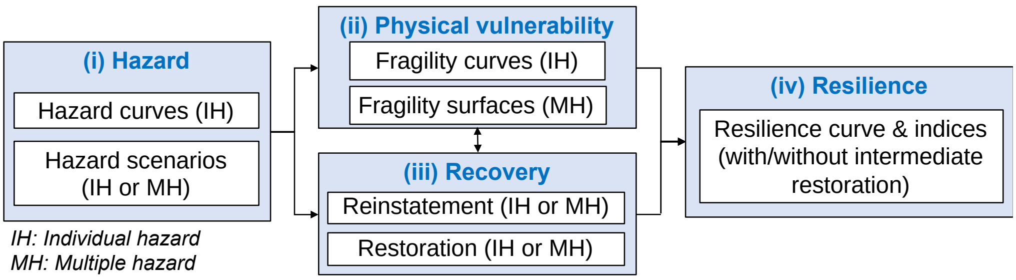


Figure 12. Main steps of the multi-hazard resilience assessment framework

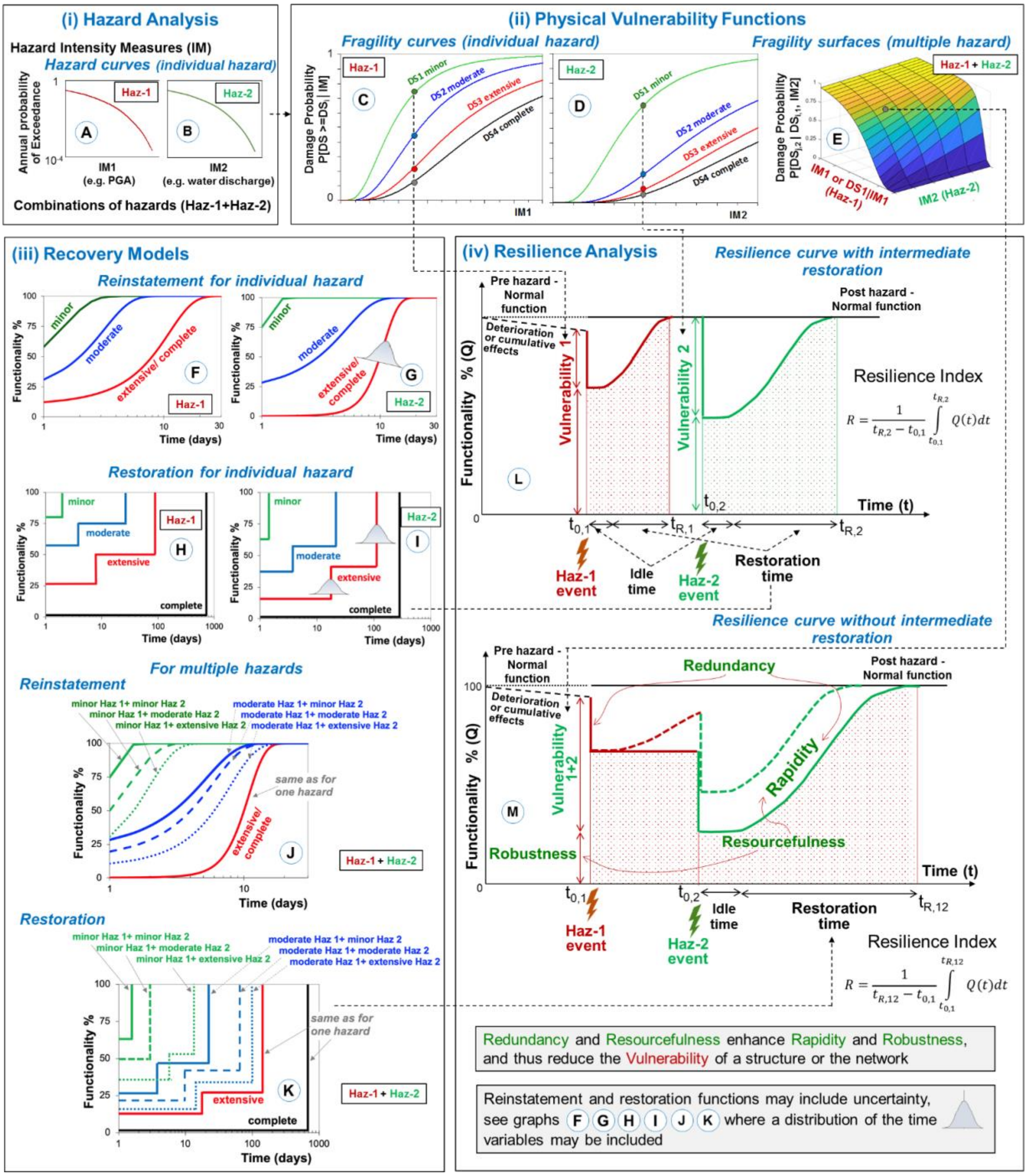


Figure 13. Multi-hazard resilience assessment framework including: (i) hazard analysis, (ii) physical vulnerability, (iii) recovery, and (iv) resilience analysis (Argyroudis et al. 2020a).

This framework was made adaptive to facilitate timely and cost-efficient management for allocating the resources reasonably and enabling adjustments to the initiation and the type of restoration, the later depending on the hazard(s). This is reflected in the reinstatement and restoration functions, according to the stakeholder requirements and the loss of functionality after an individual or multiple hazard events. This adaptive approach accounts for the fact that mitigation measures are not always efficient across different hazards as it is further explained below. Furthermore, this approach takes into account the sequence of hazards, and its corresponding impact on the restoration models, taking into account explicitly the time of initiation of the restoration for each hazard considered (Figure 13). This analysis is performed by combining (i) the information on the identified hazards and IMs, (ii) the fragility functions for the asset at hand, and (iii) the restoration models, aiming to generate the resilience curves (Figure 13L, 13M) and to assess the corresponding resilience indices. The analysis is adaptable to different sequences of hazards: (1) A series of individual hazard events (Haz-1, Haz-2), where the second hazard occurs after the consequences of the first hazard have been recovered, corresponding to Figure 13L, including for example independent hazards of different or same nature within a relatively long period. (2) The second hazard (Haz-2) occurs without (continuous line in Figure 13M) or partial (dashed line in Figure 13M) damage restoration after Haz-1, including for example correlated or independent hazards of the same or different nature.

In this WP new collaborations initiated with Prof D Frangopol (Lehigh University, USA), Dr MA Zanini, Dr L Hoffer (University of Padova, Italy), Dr E Tubaldi (Strathclyde University, UK). These collaborations resulted to two publications (Argyroudis et al. 2019c, Argyroudis et al. 2020a).

Task 4.1: Estimation of network losses A roadmap for resilience assessment of critical infrastructure at the network and national scale was proposed, based on the framework described above. In particular, the framework described in Figure 13 can be adjusted, extended and applied to the entire highway infrastructure of a region or a country as per Figure 14, i.e. to a portfolio of critical highway assets such as bridges, tunnels, embankments, slopes or retaining walls. Likewise, it can be employed in the resilience evaluation of critical infrastructure, such as hubs, ports, airports, railways, electric power or gas networks toward community resilience. This roadmap in achieving resiliency in regions, countries or continents, is aligned with international frameworks and policies for disaster risk reduction, e.g. UNISDR, 2015; NIST, 2016; Lloyd's Register Foundation, 2019. In this respect, the resilience assessments for single or multi-hazard events at infrastructure scale can be utilised by the network operators and owners to prioritise the mitigation measures, including retrofitting and/or monitoring of critical assets, optimisation of recovery strategies and disaster preparedness, insurance of the infrastructure against losses from natural and/or human-induced disasters, and planning for extending infrastructure. Decision making may be based on the resilience assessment, accounting for critical interdependencies between networks, and other factors, such as socio-political criteria, the impact of infrastructure failures to businesses, populations and environment.

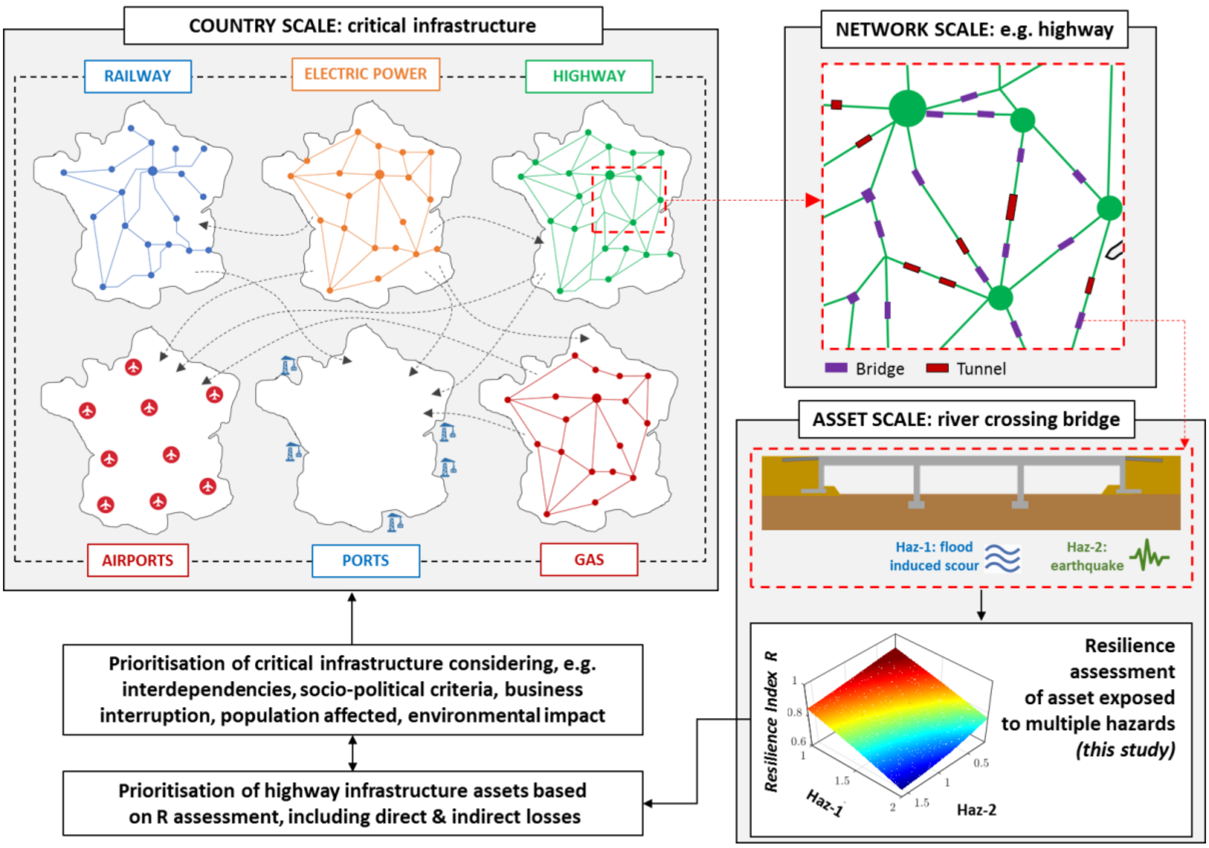


Figure 14. Roadmap of asset-specific resilience-based assessment providing information to network operators and countries for decision-making in resources allocation (Argyroudis et al. 2020).

Estimation of direct and indirect losses

The resilience assessment described above is extended to include direct and indirect losses for given hazard scenarios (Argyroudis et al. 2020d), which is specified in Figure 15 for bridges (SoA2). Direct cost (C_D) due to bridge damage represents the repair costs, evaluated by multiplying the damage probabilities at various damage states DS_i, with damage ratios (DR) and replacement cost of the asset (C). The indirect cost (C_{IN}) due to loss of the bridge's functionality, is commonly calculated accounting for the additional costs due to the detour of the traffic. The indirect cost associated with a detour on a bridge can be evaluated as the summation of the operating cost of vehicles on detour (C_{op}) and the cost due to vehicle time loss (C_{TL}) caused by the bridge damage. Also, a new cost-based resilience index was introduced, accounting for the effect of indirect losses in the resilience of the assets (see Task 4.2)

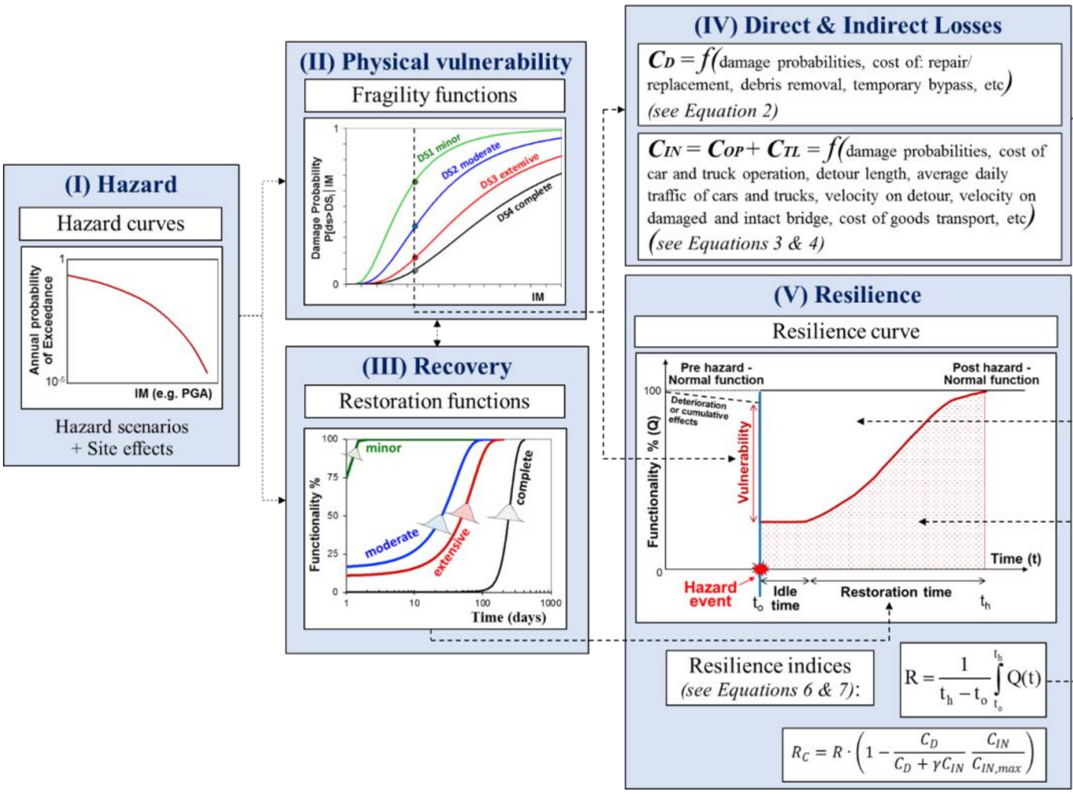


Figure 15. Resilience assessment framework inclusive of direct and indirect losses (Argyroudis et al. 2020d)

Restoration models for bridges exposed to flood and scour effects

A comprehensive survey was conducted, which elicits knowledge from experts in an effort to develop restoration and reinstatement models for scour critical bridges. This effort of data collection aims to produce reliable resilience models for representative bridges. In particular, a comprehensive questionnaire was prepared, and a survey was conducted as a means to develop restoration functions for bridges exposed to scour effects. questionnaire covers the restoration tasks of any river crossing bridge with spread or piled foundations. The deck of the bridge is considered to be either continuous or simply-supported. The pier to deck and abutment to deck connection is considered to be either rigid or through bearings. The number of spans and the geometry of each structural component were not considered in this questionnaire due to their variability. The reference bridge of this questionnaire has a total length of 101.5m and three equal spans of 33.5m (Figure 16).

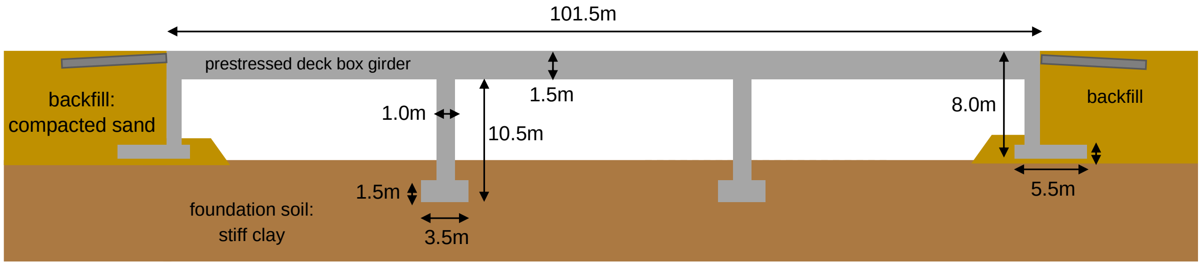


Figure 16. The 3-span prestressed concrete reference bridge

The experts were requested to provide their estimates for different levels of damage, i.e. minor, moderate, extensive and complete, for the different bridge components, i.e. foundations, piers, abutments & wingwalls, bearings, deck, backfill & approach slab. The damage levels are guided by sketches and quantitative description of the damage for each bridge component as is illustrated in Figure 18 and Figure 19. The experts were requested to provide for each level of damage for each component, the following estimations (Figure 17):

- **idle time** (column 2, 3), i.e. an estimate of the minimum and the maximum time before the initiation of any restoration work. This time might include, but is not limited to emergency response, removal of standing water, inspection and condition assessment, site investigation, structural and foundation evaluation, design of measures, including organisational barriers. This time does not include any work or construction on the bridge.
- **traffic capacity of the bridge after damage (% of the normal bridge capacity)** (column 4), is the metric of "traffic restriction" for the bridge for each level of damage and for each point in time after the commencement of the restoration works. The experts were asked to provide the expected traffic carrying capacity (0, 50 or 100%) at time 0, 3, 15, 30, and 60 days following the initiation of restoration works. The selected % traffic capacity, accounts only the effect of damage of that specific component to the functionality of the bridge, e.g. when considering bearings, it is assumed that columns, footings, and abutments are intact. On day 0, the traffic capacity is linked solely on the structural capacity of the bridge structural components, except the case of the deck, which might include non-structural obstructions, e.g. accumulation of water or debris that obstruct the traffic. Thus, the traffic capacity on day 0 is the remaining capacity of the bridge before any restoration task commences.
- **restoration task(s)** (column 5), i.e. the repair tasks that may be applied in order to recover the bridge component to its normal operation based on a list of tasks R_i given to the experts.
- **cost ratio** (column 6), i.e. an estimation for the cost of the repair tasks defined in column 5, as a ratio of the construction cost of the entire bridge.
- **comments**: the experts can provide comments on other component damage (deck, columns/piers, abutments, or foundation) that they might expect to see along with the component damage that is considered.

This survey is on-going (see also Mitoulis et al. 2019) and a journal publication is under preparation (Miitoulis et al. 2020). A representative example of restoration functions is shown in Figure 20.

Damage level (see Table 3 for description)	Idle time in days (before any restoration works)		Restoration time in days (after the initiation of the restoration works)															Restoration tasks & prioritisation (see Table 1)	Cost ratio (% of replacement cost of the bridge)
			0			3			15			30			60				
	min	max	% traffic capacity of the bridge after damage																
(1)	(2)	(3)	(4) *(check mark "X")*															(5)	(6)
			0	50	100	0	50	100	0	50	100	0	50	100	0	50	100		
Minor																			
Moderate																			
Extensive																			
Severe																			

Comments:

Figure 17. Questionnaire for one bridge component, eliciting idle time (columns 2, 3), expected level of allowable traffic capacity (%) for different damage levels (column 1) and times following the initiation of restoration works (column 4), including corresponding restoration tasks (column 5) and cost ratios (column 6). (Mitoulis et al. 2020)

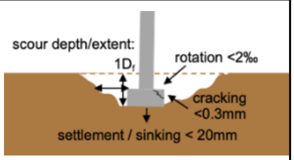
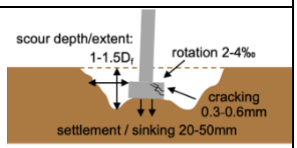
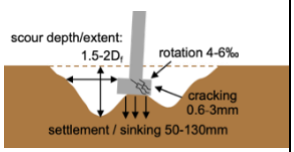
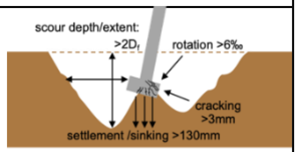
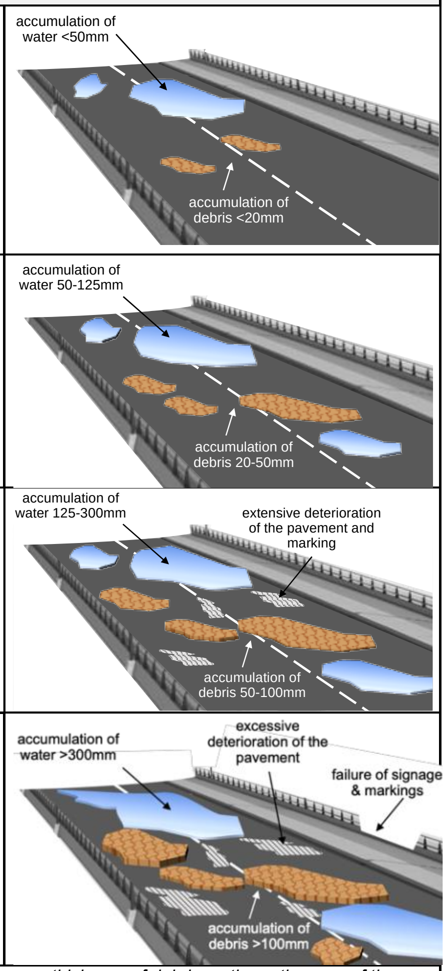
Damage level	Description	Sketch
Minor	- Foundation settlement/sinking: < 20 mm - Foundation rotation/differential settlement: < 2‰ - Minor spalling (damage requires no more than cosmetic repair): crack width < 0.3mm - Scour hole depth and extent: 1.0D_f (where D_f is the foundation depth) - Safety Factor: > 3	
Moderate	- Foundation settlement/sinking: 20-50 mm - Foundation rotation/differential settlement: 2-4‰ - Moderate cracking and spalling (foundation structurally still sound): crack width 0.3-0.6mm - Scour hole depth and extent: 1.0-1.5D_f - Safety Factor: 2-3	
Extensive	- Foundation settlement/sinking: 50-130 mm - Foundation rotation/differential settlement: 4-6‰ - Foundation degrading without collapse – shear failure (foundation structurally unsafe): crack width 0.6-3mm - Reinforcement yielding - Scour hole depth and extent: 1.5-2.0D_f - Safety Factor: 1-2	
Complete	- Foundation settlement/sinking: >130 mm - Foundation rotation/differential settlement: >6‰ - Overturning of the foundation: crack width >3mm - Reinforcement failure - Scour hole depth and extent: >2.0D_f - Safety Factor: <1	

Figure 18. Description of damage levels for hydraulic induced damage to spread foundations

Damage level	Hydraulic induced disruptions to bridge deck
Minor	- Accumulation of water due to overtopping, after extensive rainfall or flash flood: depth of water <50mm - Accumulation of debris due to landsliding of adjacent slopes or flooding: thickness of debris layer* <20mm
Moderate	- Accumulation of water due to overtopping, after extensive rainfall or flash flood: depth of water 50-125mm - Accumulation of debris due to landsliding of adjacent slopes or flooding: thickness of debris layer 20-50mm
Extensive	- Accumulation of water due to overtopping, after extensive rainfall or flash flood: depth of water 125-300mm - Accumulation of debris due to landsliding of adjacent slopes or flooding: thickness of debris layer 50-100mm - Extensive deterioration of the pavement - Extensive degradation of road markings and signage (poles, barriers, etc)
Complete	- Accumulation of water due to overtopping, after extensive rainfall or flash flood: depth of water >300mm - Accumulation of debris due to landsliding of adjacent slopes or flooding: thickness of debris layer >100mm - Excessive deterioration of the pavement - Failure of road markings and signage (poles, barriers, etc)



** The thickness of debris corresponds to the equivalent average thickness of debris on the entire area of the deck if this was uniformly distributed*

Figure 19. Description of hydraulic induced disruptions to bridge deck.

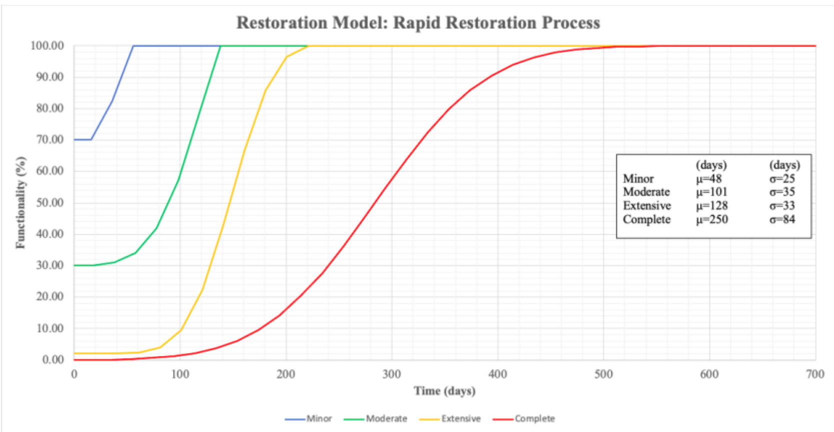


Figure 20. Example of restoration curves for hydraulic induced damage to spread foundations

Task 4.2: Loss estimation to enable decision-making

The framework described in the previous task has been applied to representative parts of highway networks exposed to individual and combined hazards to estimate losses and facilitate decision-making. The following case studies were analysed:

<u>(I) A river crossing bridge exposed to flood and earthquake events (Argyroudis et al. 2019c; Argyroudis et al. 2020a)</u>

The framework was applied to the case study shown in Figure 16 exposed to a sequence of hazard effects (flood and earthquake), which are independent hazards different in nature. Fragility functions based on the results of WP3 and restoration models based on the expert elicitation of the previous case study were used to estimate the resilience of the bridge, and in particular, the impact of consecutive hazards, i.e. flood and earthquake events, on the bridge resilience index. For this application, it was assumed that flood hazard occurs first (Haz-1) and earthquake second (Haz-2). Moreover, the earthquake event is assumed to happen before or after the end of the recovery process following a flood. All cases are investigated by assuming three different scour levels, $1.0D_f$, $1.5D_f$, and $2.0D_f$ (where D_f is the foundation depth of the pier footing) and five levels of peak ground acceleration (PGA), 0.2g, 0.4g, 0.8g, 1.2g and 1.6g. Figure 21 shows the results of the first case in which seismic scenarios of different magnitude are considered to occur after the complete bridge recovery from Haz-1. In all cases, namely $1.0D_f$, $1.5D_f$ and $2.0D_f$, the time needed for recovering from the flood is significantly higher than the time for the full restoration for any PGA level. However, the loss of functionality due to Haz-1 is limited when compared to the one caused by the higher PGA levels. In general, the resilience of the bridge decreases with increasing levels of scouring and PGA.

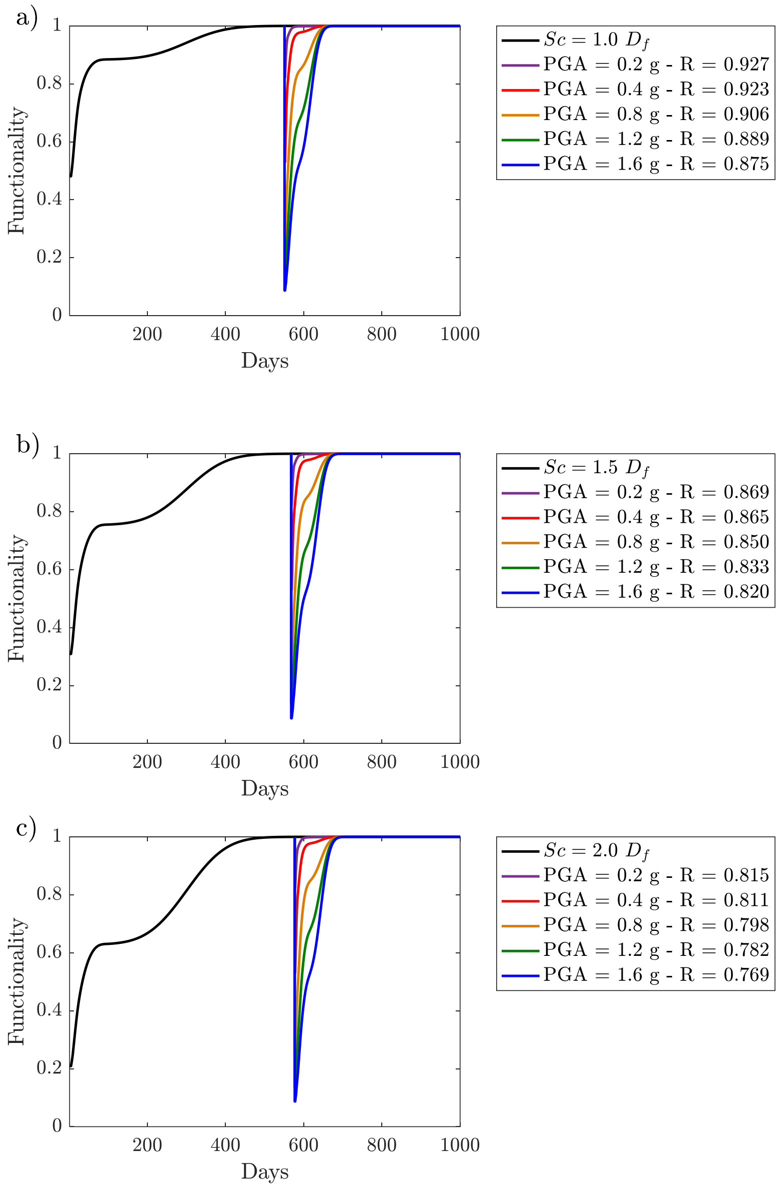
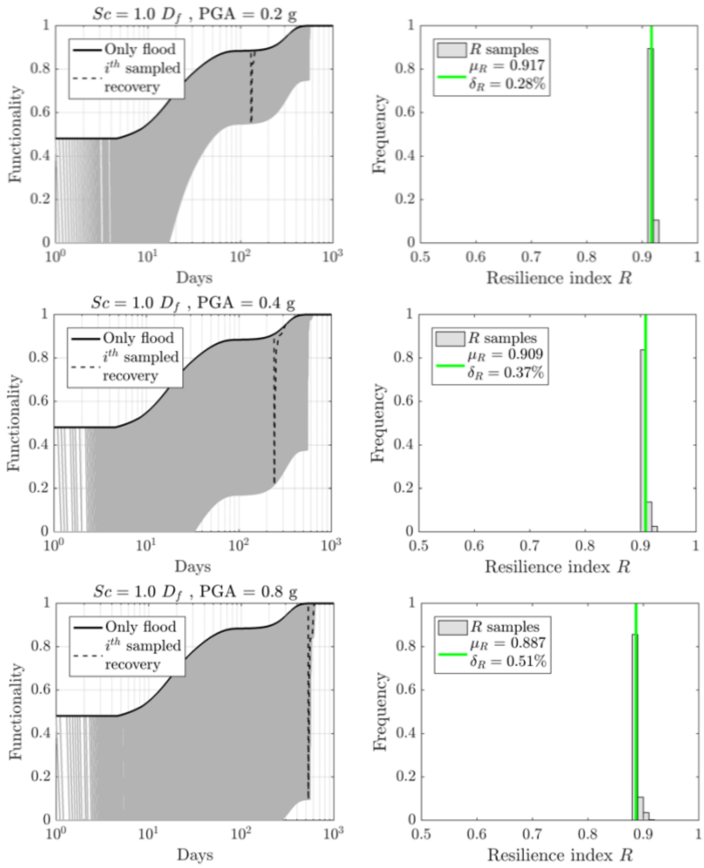


Figure 21. Resilience curves for the case that Haz-2 (EQ at PGA levels equal to 0.2. 0.4, 0.8, 1.2 and 1.6 g) occurs after the total recovery from Haz-1: a) Sc = $1.0D_f$, b) Sc = $1.5D_f$, and c) Sc = $2.0D_f$ (Argyroudis et al. 2020a).

The second case considered corresponds to the occurrence of Haz-2 when the recovery from the previous calamitous event is still ongoing. This second case is more complex than the first since the effect on the total bridge recovery is strongly influenced by the temporal occurrence of the seismic event. Since the time of occurrence of Haz-2 is a random variable (RV), the restoration process and the resilience index R itself becomes random. For computing the distribution of R, the time of occurrence of Haz-2 has been uniformly sampled in the time interval between the occurrence of Haz-1 and the time of total recovery from Haz-1. Figure 22 shows the effects of five different levels of PGA, randomly occurring during the recovery from Haz-1. In particular, in the case with the lower level of PGA, i.e. 0.2 g, a minor shaking soon after the flood is sufficient for dropping the bridge functionality to zero. This is caused by a combination of a low post-flood initial functionality and high bridge seismic vulnerability due to the short time between the two hazards occurrence. For all five cases, the effect of the earthquake on the resilience lowers when it occurs a long time after the occurrence of the previous Haz-1, and this is clearly shown by the grey curves representing the entire sampled recovery curves. For high PGA levels, greater than 0.8 g, the residual functionality drops to zero even when the earthquake occurs almost at the end of the restoration process. Figure 23 shows the behaviour of the expected value of R, E[R], and the coefficient of variation, $\delta(R)$, as a function of the scour D_f and the shaking level. For this specific case study, the trend of the resilience index can be well represented by a plane, where the expected R values decrease for increasing Sc and PGA. Regarding δ, the variable that most affects the coefficient of variation is the level of scour. Further results are available in Argyroudis et al. (2019c, 2020a).



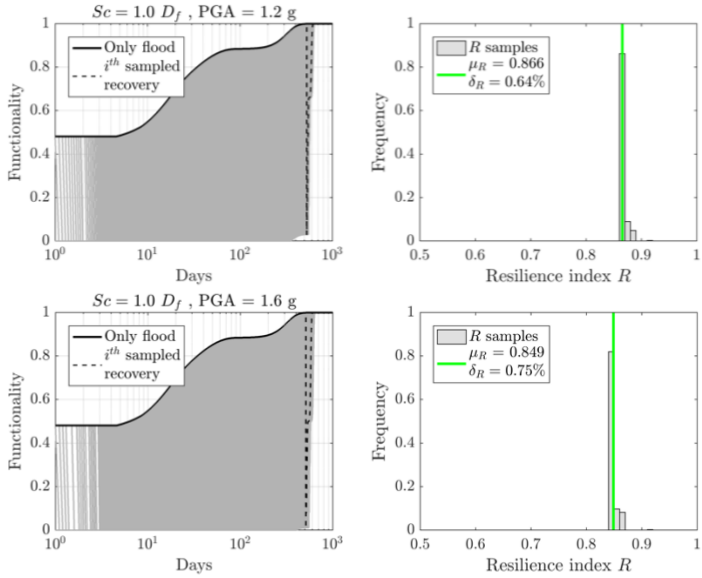


Figure 22. Resilience curves for the case that Haz-2 (EQ at PGA levels 0.2. 0.4, 0.8, 1.2, and 1.6 g) occurs during the recovery phase after Haz-1 (FL), with Sc = 1Df. The grey lines in the plots at the left correspond to the 15,000 recovery curves sampled in the time interval between the occurrence of Haz-1 and the total recovery from Haz-1. μ_R and δ_R in the plots (right), correspond to the central value and the coefficient of variation of the estimated resilience indices (Argyroudis et al. 2020a).

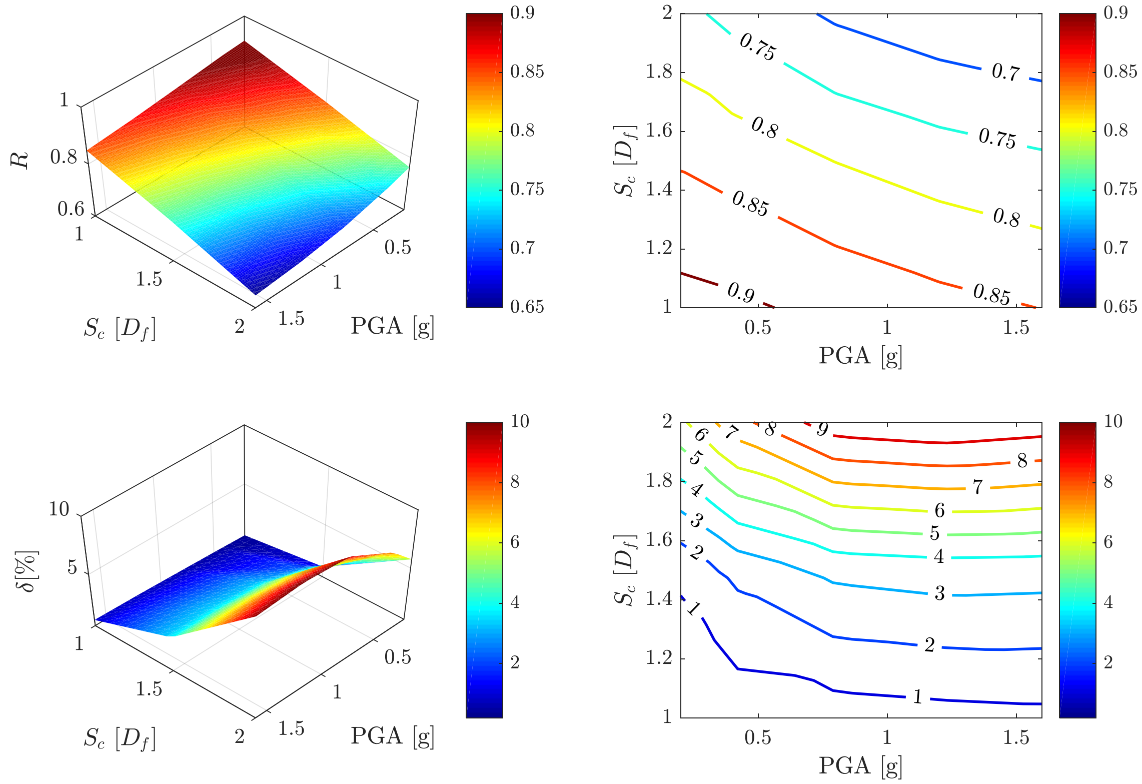


Figure 23. Behaviour of the resilience index, μ_R, (plots at the top) and the coefficient of variation, δ, (plots at the bottom) as a function of the scour (Sc) and the shaking level (PGA) (Argyroudis et al. 2020a).

<u>(II) A portfolio of bridges located at the ring road of Thessaloniki, exposed to seismic effects</u>

The framework of Task 4.1 was applied for assessing the resilience of representative bridges in Thessaloniki, Greece, exposed to earthquakes (Table 2). The three bridges of this case study are analysed for two seismic scenarios (Nasiopoulos et al. 2019, Argyroudis et al. 2020d). The first one refers to an earthquake with a probability of exceedance equal to 10% in 50 years (Scenario I) corresponding to a return period of 475 years and the second with probability 5% in 50 years (Scenario II) corresponding to a return

period of 975 years. The application quantifies the robustness of the bridges against different seismic hazard scenarios, by utilizing realistic fragility functions and the rapidity of the recovery and/or retrofitting after the occurrence of a certain degree of damage, based on realistic restoration functions. Both direct losses due to structural damage and indirect losses due to traffic disruption are included in the analysis (Table 3). For the estimation of the indirect losses (C_{IN}) due to traffic deviations, an alternative detour is proposed for each one of the examined bridges, as shown in Figure 24. Two different approaches for the modelling of the restoration tasks were examined: a linear (deterministic) as per FEMA (2009) and a cumulative normal distribution one (stochastic) on the basis of a Monte-Carlo simulation. Realistic repair tasks and distributions of repair durations were considered based on engineering judgement considering realistic local construction practices. The resilience curves were generated for the two scenarios (Figure 25). For the deterministic analysis, these curves are plotted considering the post-event functionality, the idle and the repair time, weighted with the probability of occurrence of each damage state. In the stochastic analysis, the resilience curves are based on a mean and standard deviation of the restoration time, weighted with the probability of occurrence of each damage state. Regarding the R values for different bridge types and locations, the curved in-plane bridge (Bridge 3) has the lowest resilience. This is reflected both by the vulnerability of the structure, which leads to higher loss of functionality, and time-consuming restoration actions also related to the difficulty in accessing the bridge, because this is an overpass of the busy ring road of the city, which makes any restoration tasks more challenging. The other two bridges have similar resilience. In regard to the impact of indirect losses to the resilience of the three bridges, Bridge 2 is most critical, followed by Bridge 1 and Bridge 3. This is due to the higher vulnerability of Bridge 2 and the longer detour length for this particular bridge.
As the loss in resilience is not a measure of the direct and indirect monetary losses, a new resilience index was introduced, R_C, which encapsulates socio-economic consequences (direct and indirect losses) in the resilience assessment. R_C is the streamlined R index decreased by two factors. The first one is related to the socio-economic importance of the indirect loss of the examined bridge compared to its direct one, while the second factor normalizes this indirect cost of the bridge in accordance with the maximum indirect cost of the examined portfolio. The R_C values calculated in the present study are compared with the R values in Table 4, for the two seismic scenarios. It is observed that the higher impact of the indirect losses is estimated in the resilience of Bridge 2.

Table 2. Portfolio of bridges along the ring-road of Thessaloniki

Bridge		Location	Construction Method	Construction Year	Spans	Length/ Width (m)	Foundation Type
1		Neapoli's Valley	Precast I-beams with continuous deck slab	1984	3	120/ 22	Shallow
2		Interchange K12	Cast in-situ box girder deck	1992	3	77/ 14	Piles
3		Interchange K8	Cast in-situ box girder deck	2002	7	147/ 11	Shallow

The value of the proposed framework and application at the asset level is the encapsulation of the direct and indirect losses and recovery process in two indices, which can facilitate the efficient allocation of resources, planning and interventions by the owners, toward safer and more resilient transport infrastructure. Thus, it is essential for the owners to define, with the help of engineers, appropriate thresholds for the resilience indices to expedite the decision-making according to their needs and priorities. The proposed framework and indices are of particular interest for, but not limited to, controlled access motorways such as a ring road of a city or a high-speed road, where there are not many alternative routes.

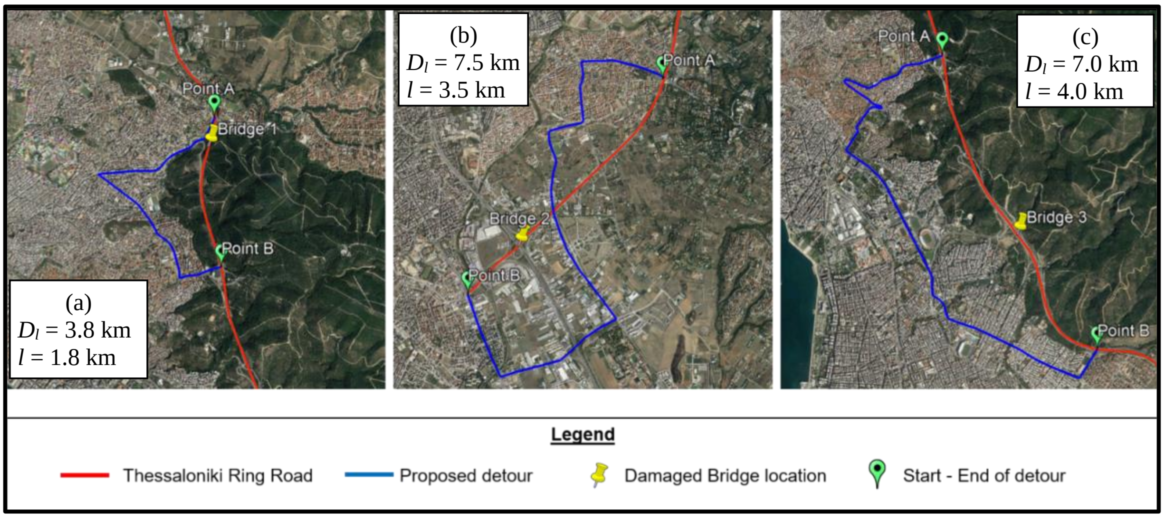


Figure 24. Alternative detours for (a) Bridge 1, (b) Bridge 2 and (c) Bridge 3. D_l is the detour length (blue line) and l is the length of the link (distance from point A to B on the red line).

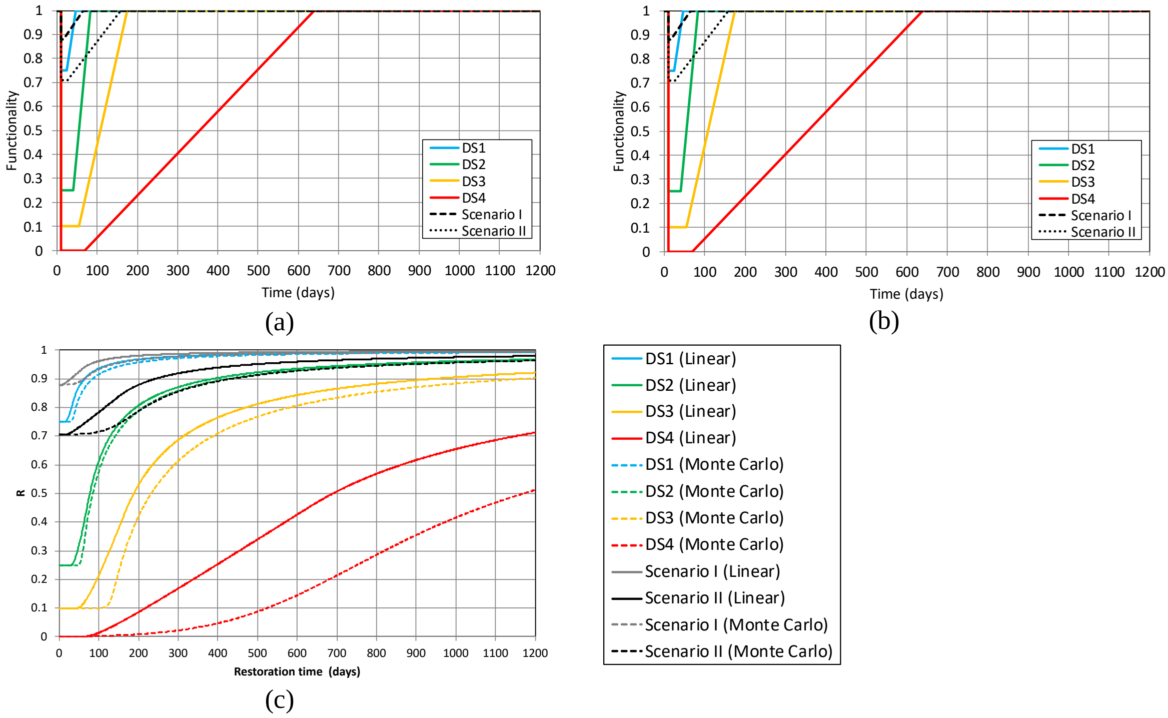


Figure 25. Representative resilience curves for Bridge 1: Deterministic linear (a) and stochastic Monte Carlo (b) restoration and resilience curves and temporal variation of resilience ratios (c).

Table 3. Direct (repair) and indirect costs of the Thessaloniki's Ring Road examined bridges

Bridge	**Scenario I**				**Scenario II**			
	Direct (C_D)	Indirect (C_{IN})	Total (C_{TOT})	Ratio (C_{IN}/C_D)	Direct (C_D)	Indirect (C_{IN})	Total (C_{TOT})	Ratio (C_{IN}/C_D)
1	\$ 264,651	\$ 545,416	\$ 810,067	2.1	\$ 702,279	\$ 2,116,326	\$ 2,818,605	3.0
2	\$ 612,670	\$ 13,137,513	\$ 13,750,183	21.4	\$ 928,214	\$ 22,368,967	\$ 23,297,181	24.1
3	\$ 385, 525	\$ 4,444,235	\$ 4,829,760	11.5	\$ 606,013	\$ 7,145,407	\$ 7,751,420	11.8

Table 4. Cost-based resilience indices (R_C) for the examined portfolio of bridges

Bridge	Scenario I			Scenario II		
	R	R_C	R_C/R	R	R_C	R_C/R
1	0.997	0.965	0.968	0.980	0.916	0.935
2	0.914	0.697	0.763	0.848	0.664	0.783
3	0.964	0.939	0.974	0.939	0.831	0.885

(II) The Queensferry Crossing bridge in Scotland, exposed to accumulation of ice

The Queensferry Crossing was opened in August 2017, replacing the Forth Road Bridge, which was itself opened in September 1964. One of the main purposes of the new bridge was to reduce the number of closures due to, for example, wind and to thus increase the resilience of the critical A90/M90 link from Edinburgh to Perth, Fife and the north-east of Scotland. The first weather-related closure of the Queensberry Crossing was in February 2020 when ice that had formed on the superstructure fell to the carriageway creating a safety risk for road users. The bridge was closed for 36 hours and in this case study the economic consequences of the closure based on the framework of Figure 15 and available data were estimated (Table 5). The diversion routes can be seen in Figure 26. The total economic consequences (C_{TOT}) is the sum of repair loss (C_{REP}), running loss of the detouring vehicles (C_{Run}), time loss due to the unavailability of the highway segment (C_{TL}), and environmental loss (C_{EN}).

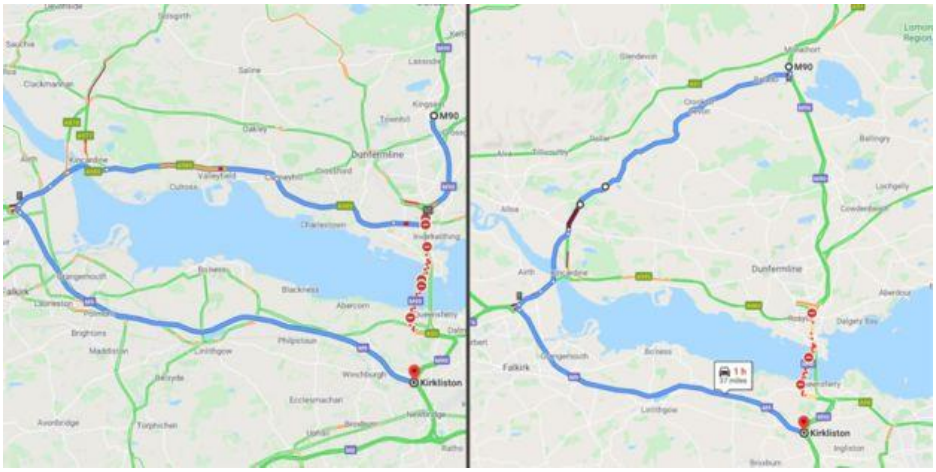


Figure 26. Diversion routes across the Kincardine Bridge during the closure of Queensferry Crossing from 17 to 19 February 2020

Table 5. Estimated economic consequences

Cost	Total (1.5 days) [£]	Per day [£]
Operational cost associated with the detour, (C_{Run})	3,051,472	2,034,315
Cost of time loss for users and goods traveling through the detour, (C_{TL})	3,571,034	2,380,689
Environmental cost of Co2 emissions, (C_{EN})	329,774	219,849
Total economic consequences, (C_{TOT})	6,952,279	4,634,853
Project value	1,350,000,000	
Losses to project cost ratio	0.51%	

Since the closure was only for 36 hours the Queensferry Crossing can be seen as a resilient asset compared to its predecessor. However, due to the dependency on the asset and that it is fundamentally a backbone of the transportation network in Scotland, even low duration closures can cause significant social, economic,

and environmental costs and impacts. This estimate could be used to compare against previous closures on the Forth crossing road bridge to see how much the costs incurred from closure have changed, therefore giving a quantitative indication of the improved resilience of the Queensferry Crossing compared to the Forth Road Bridge. This could also be extended to examine potential mitigation measures to prevent closure from occurring or to reduce the restoration/closure time of this critical transportation asset.
In this case study the industrial partner TRL participated (Prof MG Winter), and Transport Scotland provided with feedback and data. A journal paper is under preparation (Smith et al. 2020).

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Argyroudis S, Winter MG, Mitoulis S (2019b). Transportation infrastructure ecosystems and their vulnerability to geohazards. XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik Iceland, 1-6 September.

Argyroudis S, Hofer L, Zanini MA, Mitoulis S (2019c). Resilience of critical infrastructure for multiple hazards: Case study on a highway bridge. 2nd International Conference on Natural Hazards & Infrastructure (ICONHIC), Chania, Greece, 23-26 June.

Argyroudis S, Mitoulis S, Kaynia AM, Winter MG (2018a). Fragility assessment of transportation infrastructure systems subjected to earthquakes. Geotechnical Earthquake Engineering and Soil Dynamics V, June 10-13, Austin, Texas, USA, Geotechnical Special Publication (GSP 292), pp 174-183

Argyroudis S, Mitoulis S, Winter MG, Kaynia AM (2018b). Fragility of critical transportation infrastructure systems subjected to geo-hazards. 16th European Conference on Earthquake Engineering, June 18-21, Thessaloniki, Greece.

Argyroudis SA, Mitoulis SA, Hofer L, Zanini MA, Tubaldi E, Frangopol D (2020a). Resilience assessment framework for critical infrastructure in a multi-hazard environment. *Science of the Total Environment*, 136854

Argyroudis SA, Mitoulis SA (2020) Vulnerability of bridges to multiple stressors: floods and earthquakes, Reliability Engineering and System Safety (under preparation 70%)

Mitoulis SA, Argyroudis S, Loli M, Imam B (2020). Restoration functions for assessing the resilience of scour critical bridges. *Engineering Structures*. (*under review)*

Argyroudis SA, Nasiopoulos G, Mantadakis N, Mitoulis SA (2020d). Cost-based resilience assessment of bridges subjected to earthquakes. International Journal of Disaster Resilience in the Built Environment, DOI 10.1108/IJDRBE-02-2020-0014.

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Yuan V, Argyroudis S, Tubaldi E, Pregnolato M, Mitoulis S (2019). Fragility of bridges exposed to multiple hazards and impact on transport network resilience. SECED2019 Earthquake risk and engineering towards a resilient world, Greenwich, 9-10 September.

1.3 Impact

TRANSRISK paved the pathways to innovation in resilience engineering by providing a breakthrough in three main areas of research and advancing the current state of the art as follows.

- Delivered a primer in resilience engineering by establishing a novel resilience assessment framework for transport infrastructure that accounts for the nature of the hazards, including projections for exacerbation of effects due to climate change, their sequence, the loss of functionality, the recovery strategies and their rapidity and associated losses.
- Developed adaptable three-dimensional fragility models illustrated in novel fragility surfaces for facilitating the assessment of the vulnerability of transport systems of assets (SoA) exposed to multiple hazards.
- Built advanced four-dimensional numerical models of transport SoA subjected to critical hazards, which included the three dimensions of the SoA geometry, but also the evolution of models due to deterioration and/or accumulation of natural hazard stressors on the asset throughout their lifetime.

In this respect, TRANSRISK complemented and diversified the Fellow's knowledge and skills in the niche area of infrastructure resilience. The **impact of TRANSRISK** in academia, industry and society as well as in the Fellow's career development is described in the following.

Participation is research projects and continuation plan

As part of TRANRISK research, the Fellow participated in H2020-SERA-TA **DYMOBRIS** project that provided him with insights into the response of scoured structures to dynamic loads, through large-scale testing. The above research is currently extended to data-driven resilience assessment based on aerial and terrestrial monitoring systems through the participation of the Fellow in H2020-MSCA-IF-2018 **BriFace project** and a state-of-the-art paper is under review. This research will be further extended through the Fellow's active involvement in H2020-MSCA-IF-2019 **ReBounce project**, which will study the resilience of infrastructure on a network scale considering climate change effects. This is expected to have a significant impact on the well-informed resilience-based management/maintenance of infrastructure, and hence, in minimising losses and improving provided services and quality of life. Also, the Fellow co-supervises a **PhD project** funded by the Tertiary Education Trust (TETFUND) **ResilienTTS:** Resilience of transport hubs exposed to diverse hazards considering interoperability of systems and participates on an **Innovate UK 2020** with the SME Winter Associates Limited, on Novel risk analysis tools for transport infrastructure exposed to geohazards. The above research activities are a continuation of TRANSRISK project, and they are expected to facilitate resilience-based management, of critical infrastructure, including the impact of climate change toward sustainable development. Also, to provide commercial solutions, through the industry-academia collaborations, toward effective problem-solving of complex challenges in critical infrastructure sector. This research developments respond to **urgent security** and **socio-economic needs of the EU** and align with the strategic priorities of the Horizon 2020, i.e. see Societal Challenges*: Secure societies-Protecting freedom and security of Europe and its citizens*, to "*enhance the resilience of society against natural and man-made disasters and develop novel solutions for the protection of critical infrastructure*", and thus is aligned to the UN's Sustainable Development Goals.

Contribution to research proposals

The Fellow considerably improved his understanding of the research and industrial environment and needs as he was heavily involved in the **write-up of research grants** on risk and resilience assessment of critical infrastructure exposed to diverse hazards, including communication with partners

- **H2020-MSCA-RISE-2019,** multi-partner project on monitoring-enhanced resilience assessment of energy and transport infrastructure - *decision pending* (*Budget:* €~1m, *PI: Dr S Mitoulis*)
- **Innovate UK 2020 with the SME Winter Associates Limited,** on Novel risk analysis tools for

transport infrastructure exposed to geohazards - *successful (Budget: £8.5k, PI: Dr S Mitoulis)*

- **H2020- LC-CLA-16-2020**, with a 17 partners consortium on Multi-hazard risk management for risk-informed decision-making in the E.U. – *decision pending (Total budget: €5m, PI: Dr S Mitoulis)*
- **Marie-Curie MSCA-IF 2019** with Dr M Loli on Resilience of bridges exposed to hydraulic hazards - *successful/funded (Budget: £165k, Supervisor: Dr S Mitoulis, I am co-supervisor of the research fellow)*
- **Marie-Curie MSCA-IF 2019** with Dr S Stefanidou on Resilience of transport hubs exposed to natural and human-induced hazards - *successful/not funded (Budget: £175k, Supervisor: Dr S Mitoulis)*
- **Newton fund - Researcher Links Workshops** with Tongji University, China, on Disaster risk prevention & resilience enhancement for critical civil infrastructure using digital technologies - *will be submitted* in *Aug 2020 (Budget: £40k, PI: Dr S Mitoulis*)
- **EPSRC Standard grant** with the participation of Bristol University, ARUP, JBA Trust, HR Wallingford, Maccaferri, Transport Scotland, Network Rail, RSSB and Devon County, on the vulnerability and resilience of bridgeworks exposed to hydraulic hazards – *unsuccessful (Budget: £890k, PI: Dr S Mitoulis)*
- **SERA** (H2020-INFRAIA-2016-1) - Transnational Access to Experimental Facilities/3rd call, with Strathclyde University, on the dynamic identification and monitoring of scoured bridges under earthquake hazard – *successful (Budget: £20k, I am a Co-I)*
- **Marie-Curie MSCA-IF 2018** with Dr Mayoral from UNAM (Mexico) on the resilience assessment of transit transfer stations – *received a seal of excellence 92.2% (Budget: £165k, Supervisor: Dr S Mitoulis)*

Secondments and research collaborations

The following secondments, meetings and research collaborations have been realised during the project:

- Secondment to **Transportation Research Laboratory (TRL**), Edinburgh, UK (February 2018), and collaborated with Prof MG Winter, on geo-hazard effects to highway infrastructure.
- Collaboration and interaction with Dr AM Kaynia in the **Norwegian Geotechnical Institute (NGI)** throughout the course of the project with substantial online meetings and interactions, for the advanced numerical modelling of transport infrastructure subjected to geo-hazards. It was assessed and decided that the planned work can be fully developed and delivered remotely (emails, online meetings).
- Participation in the organisation of meetings with **industrial partners** such as ARUP (Dr J Mian, S Carluccio and Resilience Shift project), Network Rail (S Abbott), Highways England (M Pooley, V Pierfrancesco), HR Wallingford (M Roca), JBA Trust (Rob Lab), and Maccafferri to disseminate the research output and to discuss collaborations, including the preparation of an EPSRC standard grant proposal. Also, collaboration initiated with **academics** in Lehigh University (Prof D Frangopol), Bristol University (Prof A Sextos, Dr M Pregnolato), Strathclyde University (Dr E Tubaldi), University of Pavia (Dr MA Zanini), and within the University of Surrey (Prof M Chryssanthopoulos, Dr B Imam, Dr Y Wang, Dr B Marti-Cardona).
- In the framework of **DYMOBRIS H2020-SERA-TA** project, participated in the large-scale testing at the Europroteas facility, Greece, 6th June 2019.

Publications and lectures

The Fellow published and/or submitted and/or currently preparing, a total of **12 journal** and **9 conference papers,** most of them as the leading author (see full list in the next section). A state-of-the-art paper has been published, together with the industrial partners of TRANSRISK project, which is expected to open-up a new research area on the vulnerability and resilience of transport infrastructure exposed to multiple hazard effects. Also, a paper with Prof D Frangopol from Lehigh University, who is a world leader in this topic, introducing and applying a new framework for the resilience analysis of critical infrastructure, considering sequences of hazards and alternative mitigation strategies. Another four journal papers on restoration and fragility of bridges exposed to hydraulic induced hazards and combined scour and earthquake hazards will be submitted within the next two months. The Fellow has organised special sessions and participated in conferences to disseminate the results of TRANSRISK project (see next section). He has been invited to deliver a **keynote lecture** on Quantification of Resilience in the "Bridges 2020" conference in Coventry (13 March 2020).

The Fellow is currently leading an opinion paper to submit to **Nature-Climate Change** with the participation of world leaders in the area of critical infrastructure aiming to highlight what's the current practices, which are the gaps and what's next in resilience engineering of critical infrastructure under climate change.

Teaching and supervision of dissertations

The Fellow has delivered lectures to UG and MSc modules on risk and resilience of critical infrastructures and he has co-supervised five UG and seven MSc research projects. For the distance learning students, he used state-of-the-art electronic means and capabilities for communicating, assessing and helping the students. He has also delivered **training seminars** to engineers, consultancies and decision makers dealing with risk and resilience-based assessments of critical infrastructure exposed to diverse stressors.

Supervision of UG and MSc research project at the University of Surrey:

- **Alec Smith** (MEng), topic: The effects of hydraulic hazards on the fragility analysis of RC bearing bridges. *A journal paper is under preparation*
- **Max Woolcott** (MEng), topic: A Resilience Analysis of Integral Bridges Subjected to Multiple Hydraulic Hazards Using 3-Dimensional Modelling
- **Pamela E Samson** (MSc Advanced Geotechnical Engineering), topic: Risk quantification of transportation infrastructure exposed to multiple hazards: vulnerability assessment of a scour critical integral bridge based on 3D numerical modelling.
- **Greg Mckenna** (DL, MSc Advanced Geotechnical Engineering), topic: Fragility analysis for highway slopes of granular material subject to multiple hazards: case study on moisture ingress and scour. *A journal paper is under review.*
- **Luther Blankson** (MEng), topic: The effects of flood induced local scour on integral bridges.
- **Arjun Baladas** (MEng), topic: Integral abutment bridges: influence of bridge-backfill interaction under seismic loading
- **Alexandru Guja** (MEng), topic: Multi-hazard fragility analysis of bridges: the impact of pier scouring on the seismic fragility of a continuous bridge system. *A journal paper is under preparation.*
- **Vincent L.F. Yuan** (MSc Bridge Engineering), topic: Fragility of bridges exposed to multiple hazards: effect of pier scour and earthquakes. *A conference paper has been published.*
- **Roman Omar** (MEng), topic: Vulnerability of an integral bridge subjected to multiple hazards with emphasis on abutment scour and subsequent earthquakes.
- **Daniel Delgado** (MSc Bridge Engineering), topic: Bridge damage under multiple hazards & repair cost state of the art review.
- **Hassan Yasin** (DL, MSc Bridge Engineering), topic: Seismic design of integral bridges: effect of bridge geometry.
- **Alexandru Guja** (MEng), summer research project funded by the EPSRC Bursary scheme, topic: Vulnerability and resilience analysis of bridgeworks exposed to multi-hazards.

Participation in Working Groups

During TRANSRISK project, the Fellow was invited to participate in the following working groups:

- University research-highway structures-hydraulic actions & extreme weather events: **Working Group in Highways England** (M Pooley) aiming to the update of DMRB document. The Fellow participated in the WG meetings on 16/11/2018, 15/5/2019, 3/12/2019.

- **Member of EAEE (European Association of Earthquake Engineering) Working Group 13**: Seismic assessment, design and resilience of industrial facilities (since 2019).
- **Vice-Chair of IABSE Task Group**: Design requirements for infrastructure resilience (since 2019).

Reviewer

The Fellow has been invited as a **reviewer** for EPSRC Centre for Doctoral Training (CDT) proposal and standard Grant proposals. He has been recently invited as a member of the Editorial Board of Sustainability Journal (Section Board for 'Hazards & Sustainability'). He has acted as a reviewer for several high-impact scientific journals and international conferences.

Training

Toward developing a greater understanding of the teaching & learning environment, the Fellow attended the following Continuing Professional Development workshops organised by the Department of Higher Education at the University of Surrey: 1) Applying Technology to Enhance Learning, 2) Student Engagement in Lectures and Seminars, 3) Introduction to Teaching and Learning, 4) Introduction to Concept Mapping, 5) Assessment and Feedback, 6) Building Confidence in Communication. He is also attending the **Graduate Certificate in Learning & Teaching programme** (GCLT) offered by the Department of Higher Education at the University of Surrey

2. Update of the plan for exploitation and dissemination of result (if applicable)

During the project, the outputs of TRANSRISK were disseminated to the scientific community, stakeholders, industry and general audiences, through various measures. All measures acknowledged the MSC actions.

(1) **Website**: the Fellow developed and maintain the www.infrastructuresilience.com website, which has attracted more than 25,000 visitors. The website has a separate webpage for TRANSRISK project providing information about the objectives, the work phases and outcomes of the project (Figure 27), and and includes information and news for the activities of the research group (Figure 28). A project page was also created in Researchgate (Figure 29).

(2) **Publications**. All publications have been published in open access repositories at the University of Surrey, and other research platforms such as the Researchgate. The MSCA funding was acknowledged.

In highly reputed scientific Journals: 3 published, 3 under review, 6 under preparation

J1. **Argyroudis** SA, Mitoulis SA, Chatzi S, Linkov I, Baker JW, Brilakis I, Gkoumas K, Vousdoukas M, Hynes W, Carluccio S, Keou O, Frangopol DM (2020). Digital technologies can enhance climate resilience of critical infrastructure (under preparation)

J2. **Argyroudis** SA, Mitoulis SA, Hofer L, Zanini MA, Tubaldi E, Frangopol D (2020). Resilience assessment framework for critical infrastructure in a multi-hazard environment. *Science of the Total Environment*, 136854 (IF: 5.589)

J3. **Argyroudis** S, Mitoulis S, Winter M, Kaynia AM (2019). Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience. *Reliability Engineering and System Safety*, 191, 106567 (IF: 4.039)

J4. **Argyroudis** S, Mitoulis S, Kaynia AM, Winter MG (2018). Fragility assessment of transportation infrastructure systems subjected to earthquakes. Geotechnical Earthquake Engineering and Soil Dynamics V, June 10-13, Austin, Texas, USA, Geotechnical Special Publication (GSP 292), pp 174-183.

J5. Achillopoulou D, Mitoulis SA, **Argyroudis** SA, Wang Y (2020). Monitoring of transport infrastructure exposed to multiple hazards: a roadmap toward resilience. *Science of the Total Environment*, 746, 141001 (IF: 3.517)

J6. Mitoulis SA, **Argyroudis** S, Loli M, Imam B (2020). Restoration functions for assessing the resilience of scour critical bridges. *Engineering Structures*. (*under review)* (IF: 3.084)

J7. McKenna G, **Argyroudis** S, Winter M, Mitoulis S (2020). Multiple hazard fragility analysis for granular highway embankments: moisture ingress and scour. *Transportation Geotechnics* https://doi.org/10.1016/j.trgeo.2020.100431 (IF: 2.385)

J8. **Argyroudis** S, Nasiopoulos G, Mantadakis N, Mitoulis SA (2020). Cost-based seismic resilience assessment of bridges. *International Journal of Disaster Resilience in the Built Environment*, DOI 10.1108/IJDRBE-02-2020-0014.

J9. Smith A, **Argyroudis** SA, Winter MG, Mitoulis SA (2020). Cost-based resilience assessment and impact of road bridge closures: Queensferry Crossing. ICE Bridge Engineering (*under review).*

J10. **Argyroudis** SA, Mitoulis SA (2020) Vulnerability of bridges to multiple stressors: floods and earthquakes, Reliability Engineering and System Safety (*under preparation 70%*) (IF: 4.039)

J11. Stefanidou S, **Argyroudis** S, Mitoulis S (2020). Fragility of bridges in a multiple-hazard environment: The effect of scour depth and ground movement. Engineering Structures. (under preparation 50%)

J12. Stefanidou S, Fragiadakis M, **Argyroudis** S, Mitoulis S (2020). Probabilistic assessment of bridges with shallow foundation in a multiple hazard environment accounting for climate change effects. *(under preparation)*

International conference proceedings

C1.Tubaldi E, Lupo R, Mitoulis S, **Argyroudis** S, Gara F, Ragni L, Carbonari S, Dezi F (2019). Field tests on a soil-foundation-structure system subjected to scour. ANIDIS2019, Italian National Association of Earthquake Engineering, 15-19 Sept.

C2.**Argyroudis** S, Achillopoulou D, Livina V, Mitoulis S (2020). Data-driven resilience assessment for transport infrastructure exposed to multiple hazards by integrating multiscale terrestrial and airborne monitoring systems, 10th International Conference on Bridge Maintenance, Safety and Management, IABMAS2020, 28 June-2 July, Sapporo, Japan.

C3.**Argyroudis S**, Hofer L, Zanini MA, Mitoulis S (2019). Resilience of critical infrastructure for multiple hazards: Case study on a highway bridge. 2nd International Conference on Natural Hazards & Infrastructure (ICONHIC), Chania, Greece, 23-26 June.

C4.Nasiopoulos G, Mantadakis N, Pitilakis D, **Argyroudis S,** Mitoulis S (2019). Resilience of bridges subjected to earthquakes: A case study on a portfolio of road bridges. 2nd Intern Conf on Natural Hazards & Infrastructure (ICONHIC), Chania, Greece, 23-26 June.

C5.Makhoul N, **Argyroudis** S (2019). Tools for Resilience Assessment: Developments, Limitations and Future Needs. 2nd International Conference on Natural Hazards & Infrastructure (ICONHIC), Chania, Greece, 23-26 June.

C6.Mitoulis S, **Argyroudis** S, Lamb R (2019). Risk and resilience of bridgeworks exposed to hydraulic hazards, IABSE2019-New York, September 4-6.

C7.Yuan V, **Argyroudis** S, Tubaldi E, Pregnolato M, Mitoulis S (2019). Fragility of bridges exposed to multiple hazards and impact on transport network resilience. SECED2019 Earthquake risk and engineering towards a resilient world, Greenwich, 9-10 September.

C8.**Argyroudis** S, Winter MG, Mitoulis S (2019). Transportation infrastructure ecosystems and their vulnerability to geohazards. XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik Iceland, 1-6 September.

C9.**Argyroudis** S, Mitoulis S, Winter MG, Kaynia AM (2018). Fragility of critical transportation infrastructure systems subjected to geo-hazards. 16th European Conference on Earthquake Engineering, June 18-21, Thessaloniki, Greece.

(3) **Outreach activities, attendance of conferences and other events** to disseminate the outcomes of the project in relevant sessions or workshops (Figure 33):

- **Invited keynote lecture** ‘Quantification of Resilience’, in ‘Bridges 2020’, Coventry, UK, 12-13 March 2020.
- **Research seminar**: ‘Resilience assessment of transport infrastructure exposed to multiple hazards’, Dept of Civil & Environmental Eng, University of Surrey, 11 February 2020.
- **SECED2019**: Earthquake risk and engineering towards a resilient world, Greenwich, 9-10 September 2019 (with presentation).
- **IABSE Congress 2019**: ‘The Evolving Metropolis: Addressing Structural Affordability, Durability, and Safety’, New York, 4-6 September 2019 (with presentation).
- **ICONHIC2019**: 2nd International Conference on Natural Hazards & Infrastructure, Chania, Greece, 23-26 June 2019 (with presentations).
- **16ECEE:** 6th European Conference on Earthquake Engineering, Thessaloniki, Greece, 18-21 June 2018 (with presentations).
- **GEESDV:** Geotechnical Earthquake Engineering and Soil Dynamics V, Austin, Texas, USA 10-13 June 2018 (with presentation).
- Resilience First’s briefing, in partnership with **Resilience Shift** funded by Lloyd’s Register Foundation, on

"Lessons learned: improving resilience in the utilities sector", ARUP London, 22 January 2020.

- "**Lloyd's Register Foundation** International Conference 2019", London, 10 October 2019.
- **EPICentre** at University College London (UCL): "Recent advances and perspectives in multi-hazard risk and resilience", 2-3 July 2019 (with presentation).
- **LoBEG** London Bridges Engineering Group AGM, 10 May 2019 (with presentation).
- Ground Related Risk to Transportation Infrastructure, **The Geological Societ**y, London, 26-27 October 2017.

(4) **Organisation of seminars and special sessions**

- **Training Courses**: on Risk and Resilience of Bridges and Networks and Critical Infrastructure, London UK, 1/3/2019, 17/2/2020 and Birmingham, UK, 1/8/2019 with participants from academic institutions, Highways England, East West Railway, Councils, London Boroughs, Transport Scotland, insurance companies, governmental bodies and consultancies (e.g. ARUP, Deltares, Ramboll) (Figure 32).
- **ICONHIC2019 Special Session:** Loss and resilience assessment tools for infrastructure exposed to natural hazards, in the 2nd International Conference on Natural Hazards & Infrastructure, ICONHIC2019 (with N Makhoul, J Lee), 23-26/6/2019, Chania, Greece.
- **IABMAS2020 Special Session 41:** Monitoring strategies for enhancing transport infrastructure resilience IABMAS2020 (with S MItoulis, D Achillopoulou, V Livina), July 2020, Sapporo, Japan *(postponed due to the pandemic).*
- **16ECEE Special Session 16**: Seismic risk and resilience of critical infrastructure (with A Sextos, F Cavalieri), in the 16th European Conference on Earthquake Engineering, Thessaloniki, Greece, 18-21/6/2018.
- **16ECEE Special Session 23**: Software for loss estimation: developments and applications (with N Makhoul, J Lee, MP Limongelli), in the 16th European Conference on Earthquake Engineering, Thessaloniki, Greece, 18-21/6/2018.

(5) A **final project report**, inclusive of main outputs and results, will be published in open access repositories at the UoS.

(6) **Posts in social media**, i.e. Facebook (Figure 30), Linkedin (Figure 31), ResearchGate. The impact of the posts was measured through the number of views and the public engagement.

Figure 27. infrastructuResilience website

Figure 28. TRANSRISK webpage in http://www.infrastructuresilience.com/transrisk/

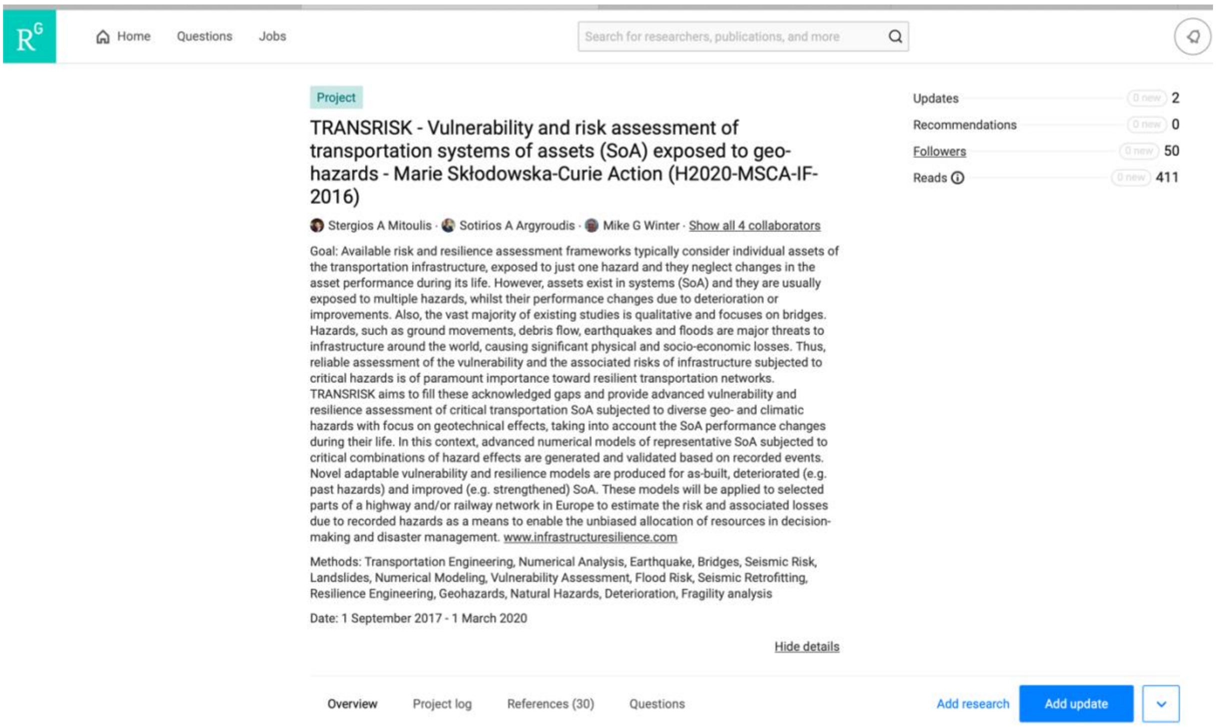


Figure 29. TRANSRISK in Researchgate (https://www.researchgate.net/project/TRANSRISK-Vulnerability-and-risk-assessment-of-transportation-systems-of-assets-SoA-exposed-to-geo-hazards-Marie-Sklodowska-Curie-Action-H2020-MSCA-IF-2016)

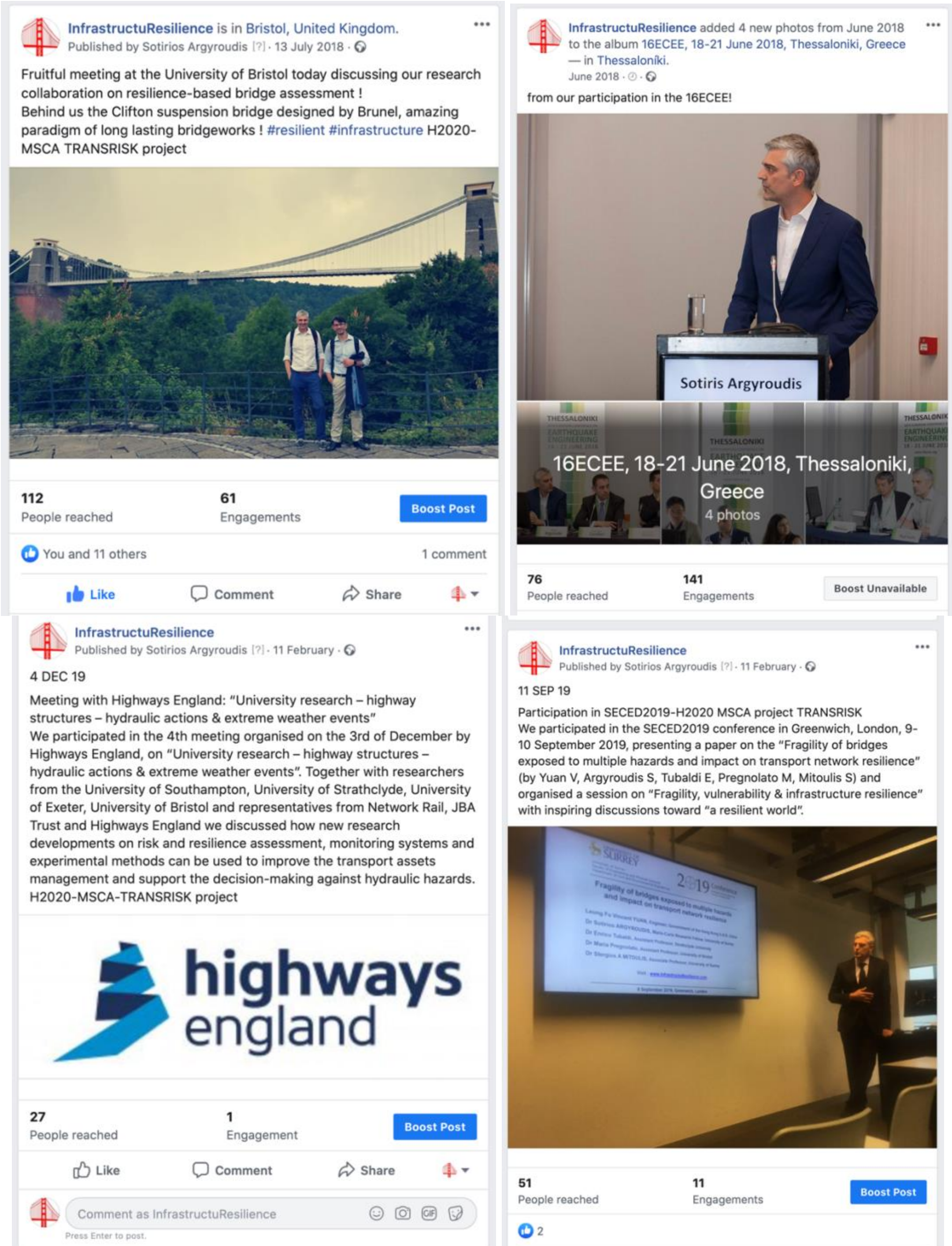


Figure 30. Examples of posts in Facebook

Dr Sotirios Argyroudis
Visiting Associate Professor at University of Surrey & Senior Research ...
11mo • Edited •

We are pleased to hear that our paper on "Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience" is accepted for publication by the Journal of Reliability Engineering and System Safety!
This is a collaborative work between our infrasrtuctuResilience https://lnkd.in/da9hPxg group Dr Stergios A Mitoulis at University of Surrey, Mike Winter (Winter Associates, formerly TRL) & Amir M. Kaynia (NGI), in the framework of TRANSRISK H2020-MSCA-IF project.
Stay tuned for the published paper.

#resilience #infrastructure #transportation #vulnerability #naturalhazards #multiplehazards

52 · 5 Comments

Like Comment Share

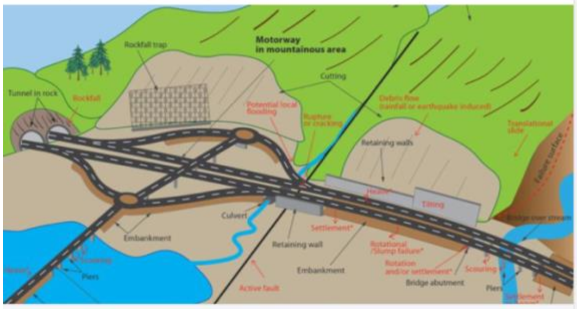
1,095 views of your post in the feed

Dr Sotirios Argyroudis
Visiting Associate Professor at University of Surrey & Senior Research ...
2mo • Edited •

I am delighted to be invited to deliver a keynote lecture on the "Quantification of Resilience" in the forthcoming 'Bridges2020' conference, which will take place in the Ricoh Arena, Coventry UK, on 12 & 13 March 2020.
The exposure of transport infrastructure to natural hazards such as floods or ground movements was proven to have severe consequences on economies and societies, which are expected to be exacerbated due to climate change. Thus, pinpointing the vulnerabilities and quantifying the resilience of infrastructure exposed to multiple hazards is of paramount importance for stakeholders, network operators and owners, toward more efficient allocation of their resources and rapid decision-making. This lecture is part of my Marie-Curie TRANSRISK research project at University of Surrey with Dr Stergios Aristotles Mitoulis : https://lnkd.in/d3WTmz9

The detailed program is available here:
https://lnkd.in/d2AfVTJ
Dave Cousins CEng MICE thank you for the invitation, and looking forward to this interesting workshop on Resilience.

#resilience #infrastructuresilience #climatechange #highwaysengland #transportscotland #bridges #Bridges2020



TRANSRISK
infrastructuresilience.com

65 · 1 Comment

Like Comment Share

3,205 views of your post in the feed

Figure 31. Examples of posts in Linkedin (continued)

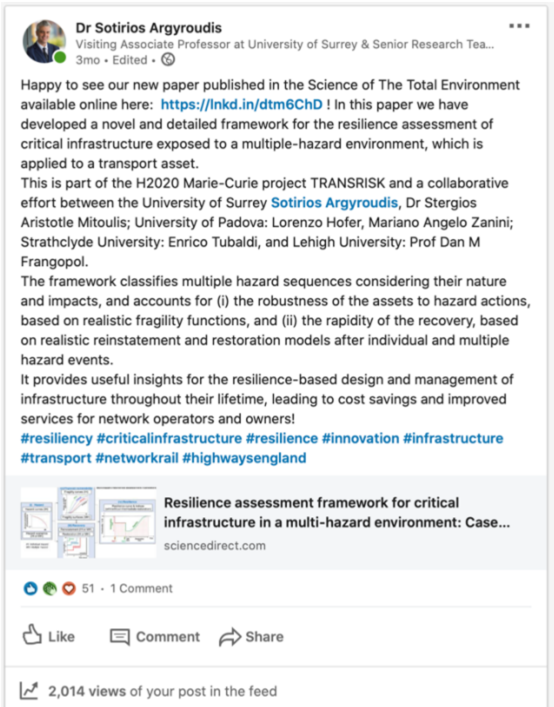


Figure 31. Examples of posts in Linkedin


Figure 32. CPD seminar in London, 17/2/2020 (left) and Birmingham 1/8/2019 (right), where TRANSRISK results were presented to senior engineers, consultants, decision-makers and network operators.

Figure 33. Participation of the Fellow and the Supervisor to networking event of Resilience Shift funded by Lloyd's Register Foundation in London, 22/1/2020 (left) and the 16ECEE, Thessaloniki, 18-21 June 2018 (right).