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Sotiris Argyroudis , Stergios A. Mitoulis , Mike G. Winter ,
Amir M. Kaynia

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Highlights

- Vulnerability assessment methods for transport infrastructure exposed to multihazards
- Hazard effects, asset typologies and fragility assessment methods, mitigation measures
- Challenges in fragility based on numerical models, emphasis on floods and earthquakes
- Novel concept of transport System of Assets in diverse ecosystems is introduced
- Current trends insights and future research opportunities in multiple hazard fragility

Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience

Sotiris Argyroudis[1], Stergios A. Mitoulis[2], Mike G. Winter[3], Amir M. Kaynia[4]

[1] Marie-Curie Research Fellow, Department of Civil and Environmental Engineering, University of Surrey, Guildford, United Kingdom, s.argyroudis@surrey.ac.uk

[2] Associate Professor, Department of Civil and Environmental Engineering, University of Surrey, Guildford, United Kingdom, s.mitoulis@surrey.ac.uk

[3] Head of Ground Engineering and Honorary Chief Scientist, Transport Research Laboratory (TRL), Edinburgh, United Kingdom and Visiting Industrial Professor, University of Portsmouth, Portsmouth, United Kingdom, mwinter@trl.co.uk

[4] Professor, Department of Structural Engineering, Norwegian University of Science and Technology (NTNU) and Discipline Leader, Norwegian Geotechnical Institute (NGI), Norway, amir.m.kaynia@ngi.no

Abstract Vulnerability is a fundamental component of risk and its understanding is important for characterising the reliability of infrastructure assets and systems and for mitigating risks. The vulnerability analysis of infrastructure exposed to natural hazards has become a key area of research due to the critical role that infrastructure plays for society and this topic has been the subject of significant advances from new data and insights following recent disasters. Transport systems, in particular, are highly vulnerable to natural hazards, and the physical damage of transport assets may cause significant disruption and socioeconomic impact. More importantly, infrastructure assets comprise Systems of Assets (SoA), i.e. a combination of interdependent assets exposed not to one, but to multiple hazards, depending on the environment within which these reside. Thus, it is of paramount importance for their reliability and safety to enable fragility analysis of SoA subjected to a sequence of hazards. In this context, and after understanding the absence of a relevant study, the aim of this paper is to review the recent advances on fragility assessment of critical transport infrastructure subject to diverse geotechnical and climatic hazards. The effects of these hazards on the main transport assets are summarised and common damage modes are described. Frequently in practice, individual fragility functions for each transport asset are employed as part of a quantitative risk analysis (QRA) of the infrastructure. A comprehensive review of the available fragility functions is provided for different hazards. Engineering advances in the development of numerical fragility functions for individual assets are discussed including soil-structure interaction, deterioration, and multiple hazard effects. The concept of SoA in diverse ecosystems is introduced, where infrastructure is classified based on (i) the road capacity and speed limits and (ii) the geomorphological and topographical conditions. A methodological framework for the development of numerical fragility functions of SoA under multiple hazards is proposed and demonstrated. The paper concludes by detailing the opportunities for future developments in the fragility analysis of transport SoA under multiple hazards, which is of paramount importance in decision-making processes around adaptation, mitigation, and recovery planning in respect of geotechnical and climatic hazards.

Keywords: fragility functions; reliability in quantitative risk analysis; highway and roadway infrastructure; numerical modelling; earthquakes; landslides; liquefaction; flooding; scouring; multiple hazards

1 Introduction

Natural hazards, such as ground movements, debris flow, earthquakes, and floods are major threats to infrastructure in many regions around the world. More importantly, societies and businesses rely heavily on transport infrastructure. In addition to the loss of life and the physical loss of the assets themselves, damage to transport infrastructure may cause significant socio-economic losses. For example, the heavy 2007 rainfall in the UK affected the road network, with the cost estimated at £60 million (The Parliamentary Office of Science and Technology, 2010); also, during the 2009 floods in Cumbria, at least 20 bridges were destroyed or damaged, causing at least one fatality, £34m of repair and replacement costs and large societal impact (Cumbria County Council, 2010). The 2012 flood events resulted in a total of 131 damaged bridges in the same region mainly due to scour (Zurich Insurance Group and JBA Trust, 2016). The 2010-2011 Canterbury earthquake sequence in New Zealand caused extensive damage to road networks due to liquefaction that resulted in settlements, lateral spreading, sand boils and water ponding on the road surfaces. Moreover, rock falls led to several road closures (Kongar et al. 2017). Extensive bridge damage was reported after the 2010 Maule earthquake in Chile due to inadequate seismic design. The effects of structural irregularity and soil liquefaction were proven to be critical for the performance of bridges (Kawashima et al. 2011). In the U.S.A, hydraulic in nature actions, such as scour and debris build-up have been established as the most catastrophic causes of bridge collapses. They represent more than 50% of the cases (US National Bridge Inventory, Cook et al. 2015), resulting in an average annual repair cost of $50m (Lagasse et al. 1995). In Europe, weather stresses represent 30% to 50% of road maintenance cost (up to €13bn p.a.); 10% of these costs are associated with effects of extreme weather events (Nemry and Demirel, 2012). As an example, flooding over large areas of the Danube and Elbe rivers in Central Europe on May-June 2013, caused road and rail closures, erosion of embankments and streets, damage to bridges and landslides blocking railways. The high-speed rail links between Frankfurt and Berlin, and between Berlin and Hannover had to be closed for repairs for several months after the event. The total economic damage was estimated at more than €12bn (MunichRe, 2013). Based on a recent international expert elicitation workshop the damage of bridges due to hydraulic causes is strongly related to the history and accumulation of predominantly scour damage (Lamb et al. 2017). As a result, undetected scour may lead to unexpected failures for flood events of smaller intensity. Among the critical threats to infrastructure around the world, scour is cited as the most common cause of bridge failure (Kirby et al. 2015). In the UK and based on a record of scour-induced failures spanning over 173 years, it is estimated that the annual probability of failure incidents is approximately 27% (van Leeuwen and Lamb, 2014). Projected changes to river flows, including climate change effects (Pant et al. 2018), would increase scour by over 8% of all the approximately 4,200 railway and 8,700 main road bridges which cross watercourses in the UK, placing them at high risk of failure (Dawson et al. 2018). Similar vulnerabilities have been identified for transport assets at estuaries or near the sea-side affected by tidal water, as well as sea level rise, which may be exacerbated due to climate change.

Multi-hazard and extreme weather effects on transport infrastructure is a strategic priority in European research and have been addressed by recent research projects. In particular, INFRARISK (Clarke and O'Brien 2016) developed a multi-hazard risk assessment methodology to perform stress testing for European transport infrastructure networks due to extreme events, i.e. earthquakes, floods, landslides, based on available fragility functions or expert judgment approaches, providing a practical and operational framework for decision making. RAIN project (O'Brien et al. 2015) identified critical land transport infrastructure exposed to extreme weather events, reviewed its failures and the current means of protecting them and developed an understanding of how infrastructure failure leads to societal vulnerability and insecurity through a risk-based decision-making framework. INTACT project (Reder et al. 2018) addressed the resilience of critical infrastructure to extreme weather events in the form of a publicly accessible Wiki and a risk management decision framework that facilitates cross-disciplinary and cross-border data sharing providing potential end-users with a means to determine the impact of extreme weather events to their infrastructure. WEATHER project (Doll et al. 2012) analysed the economic losses of extreme weather conditions, i.e. hot and cold spells, floods, landslides, wildfires, and storms, on transport systems and the wider economy and explored adaptation strategies for reducing them in the context of sustainable policy design. Similar efforts have been made in the US, to deploy resilience solutions to current and predicted future extreme weather events (Wright and Hogan 2008; FHWA 2012b; 2013; NCHRP 2014). These projects facilitate the better understanding of the impacts of natural hazards and climate change on transport systems and provide state-of-the-art knowledge on risk analysis frameworks; however, a systematic and accurate representation of the performance of transport assets subjected to geo-hazards is still lacking. Thus, reliable assessment of the vulnerability of, and the associated risks to, transport infrastructure subjected to critical hazards is of paramount importance, since it will enable the efficient allocation of resources toward resilient transport networks.

The objective of this paper is to prove a well-informed debrief of the understanding and applicability of the available methodologies for the vulnerability assessment of transport infrastructure in inter-urban environments subjected to multiple natural hazards and to identify current trends and gaps in the knowledge. This effort is directed towards enabling the enhancement of the safety of infrastructure assets toward more resilient and robust transport assets and networks. Based on the extensive literature review and to the authors' best knowledge, the results of this paper are unique, as most of the published research related to transport infrastructure focuses on the seismic fragility assessment of bridges. This review commences with an outline of the critical hazards and their effects on transport infrastructure, along with an introduction to the recent trends on quantitative risk analysis together with the design and assessment of transport assets exposed to hazards. The next section describes the common damage modes of the main transport assets. Subsequently, a review of fragility functions for transport assets under different natural hazards is provided. The review on the fragility of bridges is selective in this paper as bridges have been covered adequately in published research. In the next part of the review, the literature is summarised in terms of how different researchers have tackled the main modelling challenges in the generation of analytical fragility functions for assessing physical damage. These include the soil structure interaction and deterioration effects, the treatment of uncertainties and the modelling of multiple hazard effects. The following section introduces the concept of the infrastructure System of Assets (SoA) in ecosystems as a combination of interdependent assets exposed to diverse hazards. A methodology for the development of numerical fragility functions for SoA is also proposed. The study concludes with the gaps in the knowledge that need dire attention, and on this basis, recommendations for future developments are provided.

1.1 Natural hazards and their effects on transport infrastructure

Natural hazards and weather-related hazards have different effects on various transport assets. The impacts on the transportation system, from changes in temperature, precipitation, sea-level rise and hurricanes, along with possible adaptation strategies in the United States, are summarised in TRB (2008) and NCHRP (2014). Table 1 summarises the effects of critical geotechnical and hydraulic hazards to road transport infrastructure and possible mitigation measures. Apart from the asset-specific mitigation measures shown on the table, the following measures may be employed for any asset:

- Improve asset data knowledge and understanding, for example, for identification of high-risk locations, definition of existing vulnerabilities and interdependencies of assets and networks, which is a major challenge in the design of resilient infrastructure (Vespignani 2010);
- contingency planning measures for rapid repair and re-routing of traffic;
- monitoring of critical assets in combination with response planning;
- design of new structures to account for additional stresses exacerbated due to climate change (Stern et al. 2013), e.g. design for extremes and multiple hazards, in the context of the resilience-based design (e.g. Franchin 2018; Almufti and Willford 2013).

Table 1. The effects of critical hydraulic and geotechnical hazards on road infrastructure, and relevant mitigation measures.

Hazard	Asset affected	Damage/Impact	Typical mitigation measure
Fluvial/river flood due to extreme precipitation (including overbank and flash flooding)	Bridges over a river or stream	Scour of piers/abutment foundations (general, contraction, local scour); impact to the deck due to overtopping; failures of bank and riprap protections	Improve existing scour protection system; retrofitting of bridge foundations with additional piles (e.g. Hung and Yau 2017); bridge scour monitoring (e.g. Prendergast and Gavin 2014)
	Embankments and cuttings	Scour due to high river levels; culvert washout; slope erosion and instability, seepage of water	Improve drainage (increase ditch and culvert capacity); install geotextiles and geogrids to prevent cracking
	Pavements	Inundation, washout, deterioration, and loss of skid resistance due to excess water	Improve/maintain drainage (increase ditch and culvert capacity)
Pluvial/surface flood due to extreme precipitation	Embankments and cuttings	Settlement, sliding/slumping; swelling of clay materials	Improve/maintain drainage (increase ditch and culvert capacity); install geotextiles and geogrids to prevent cracking
	Pavements	Inundation, washout/cracking	Improve/maintain drainage (Willway et al. 2008)
Underground water	Tunnels, bridges, retaining walls	Corrosion of reinforcement; degradation of concrete strength	Improve/maintain drainage
Sea level rise and storms (flood surge)	Coastal roads, causeways over a lake or sea	Scour effects; overtopping and wave erosion, softening by soil saturation, seepage (internal erosion), piping	Renewal programme; consider sea level rise in the new designs
Landslides (rainfall or earthquake-induced, including sliding, debris flow, mudflow)	Pavements	Closure by debris flows or mudflows	Warning signs; protection measures (debris shelters, barriers, fences, ditches, tunnels); stabilization measures (e.g. reduce slope angles, rock anchors, shotcrete, jet grouting); planting of appropriate vegetation; improve drainage; removal of the exposed asset (Winter 2014)
	Cuttings, embankments and natural slopes	Slope: failures along discontinuities, toppling failure and falls, translational failure; Embankment: instability due to the failure of the foundation, failure of the material	
	Tunnel portals	Rockfalls	Rock removal; netting of rock cutting/protection barriers; rock sheds
Drought	Cuttings/slopes/ embankments	Ground stability impacts (desiccation, shrinkage of clay materials); creation of ruts	Removal of prone materials; vegetation management
Extreme hot weather	Bridge components	Expansion of the deck	Use of expansion joints; use of sliding bearings
	Signalling and Intelligent Transport Systems (ITS)	Malfunction due to overheating of power lines (indirect)	Use of uninterruptable power supplies (UPS); replacement of ageing cables
	Cuttings/embankments	Erosion, shrinkage due to soil moisture change	Use of sun sheds (slopes)
	Pavements	"Thermal fatigue"; thawing effects and cracking; melting of bitumen; loss of skid resistance	Use of geogrids; insertion of expansion joints for concrete roads to prevent "blow-ups"; application of more deformation resistant surfacings; trees not planted <15m from the road edge (Willway et al. 2008; FHWA 2015)
Wildfires	Pavements/ bridges/ tunnels/ signalling and ITS	Burning of asphalt; Failure or melting of components	Installation of high-volume sprinkler systems; replacement of wood poles and other structures with fire-resistant materials, e.g. steel or concrete

	Pavements/bridges	Limited visibility (indirect)	n/a as the risk is indirect and the hazard is addressed for all elements/assets at risk
	Natural slopes	Slope degradation and soil erosion (indirect)	n/a as the risk is indirect and the hazard is addressed for all elements/assets at risk
Snow	Pavements	Closure due to avalanches (in mountainous areas); accumulation of snow	n/a, i.e. not technical as the effect cannot be mitigated prior to the hazard
	Cuttings/slopes/ embankments	Melting of snow; slope instability	Use of snow sheds
Cold & freeze	Pavements	"Thermal fatigue"; frost heave; asphalt cracking	Sufficient thickness of pavement and non-frost susceptible base course; use of granular rock caps; remove and replace frost-susceptible subgrade; use of geotextiles/frost blankets (Willway et al. 2008; AASHTO 1993)
	Embankments	Thermal erosion; creep; heave	Backslope protection blankets using gravel or crushed stone protection layer over a geotextile
	Bridge components	Contraction of the deck	Use of expansion joints; use of sliding bearings
	Signalling and ITS	Malfunction due to low temperatures	Use of uninterruptable power supplies (UPS); use of electric heaters; replacement of ageing cables
	Slopes	Instability of rock slopes	Backslope protection blankets
Wind	Cable-stayed and suspension bridges	Aerodynamic effects (vortex shedding, galloping, flutter); turbulence	Damper systems and stiffeners; spoilers
	Signs and signals	Collapse	Strengthening equipment
	Pavements	Closure due to windblown and damaged trees	Wind warnings
Earthquake (ground shaking, ground failure due to liquefaction or fault rupture)	Bridges, tunnels, retaining walls, pavements, embankments, cuttings	Different damage modes to structural elements (piers, abutments, bearings, foundations) and geotechnical assets (settlement, heave, rotational/slump failures etc). *See section 3.*	For *bridges*: strengthening/replacement of bearings; restrainer cables; seat extension; steel, fiber composite or steel jacketing of piers; pier cap strengthening or replacement; energy dissipation devices (Buckle et al. 2006). For *approach fills* to bridge abutments: structural approach slabs; alternative materials, such as rubber-sand mixtures (Mitoulis et al. 2016; Argyroudis et al. 2016). For *tunnels in rock*: rock bolts; shotcrete or replacement of weak lining. For *tunnels in soft soil*: spot repairs; contact grouting; ground improvement; liner replacement; construct special joints. For *embankments/pavements*: compact soft or loose soils; improve foundation drainage; add berms or struts (Power et al. 2004). *For slopes/cuttings* (*see Landslide hazard*).
Any hazard that leads to impacts due to geographic interdependencies (mainly in urban environments)	Pavements	Closure due to collapse/failure of overpass bridges or adjacent buildings and/or overturn of utility poles (power, communication etc) or signalling systems Damage/closure due to failure,	Increase the distance between buildings and roads; replace pole lines with buried cables; use of durable materials for the utilities; separation of underground utility installations from roadways facilities; encasement of pipelines; increase of cover depth; provide

		leakage or explosion/fire of gas, oil, water, sewerage pipes buried under the roadway	adequate coating and wrapping of pipes/cables; joint highway and utility planning and development
	Bridges	Damage of cables (electric power, fibre-optic communication) or pipes (water, gas) carried by the bridge	Protection of pipes through coating, wrapping or fiberglass shields; provision for shut-off systems for gas, oil and hazardous material pipes

It is observed that for certain assets the fragility assessment requires a cross-disciplinary expert judgement including input from structural, geotechnical or mechanical/electrical engineering. Similarly, the mitigation measures are not solely of an engineering nature, as the contingency planning and preparedness may need the involvement of engineers and experts from other disciplines (e.g. economists, foresters, geologists), stakeholders, operators, and owners.

1.2 The concept of vulnerability and quantitative risk analysis (QRA)

Hazards refer to events related to geological, meteorological and hydrological phenomena that are characterized by intensity, spatial variability and a probability of occurrence in time. Natural hazards are independent accidental actions (EN1991-1-7, 2006). In case of transport networks, hazards and their interactions strongly depend on the geomorphological and topographical surroundings (see also section 6.1). The concept of multi-hazard design and assessment has been introduced by Bruneau et al. (2017) among others. Hitherto, no common nomenclature has been established for the phenomenally similar meaning in engineering terms between multiple hazards, multi-hazard effects, cascading, cross-hazards among others (Kappes et al. 2012). The vulnerability of transport systems is commonly assessed in terms of physical vulnerability of its components depending on the physical characteristics of the infrastructure assets, e.g. age, material, structural types, and functional vulnerability depending on the functional characteristics of the network, e.g. capacity and speed. The risk analysis of a network includes hazard identification, vulnerability evaluation of the infrastructure exposed to the given hazards and risk assessment in terms of economic, functional and social losses. The vulnerability is a fundamental component in risk analysis under any natural or climatic hazard, and its accurate estimation is essential in making reasonable predictions of losses and consequences. Risk analysis is distinguished in three levels, depending on the input data, procedures of the analysis and risk output: qualitative, semi-quantitative and quantitative (Eidsvig et al. 2017). All approaches aim to classify the most vulnerable parts of the network that require detailed analysis and to provide support for planning, preparedness, and prioritization of risk-reduction measures. In the first approach, hazard and vulnerability are described through qualitative estimates using descriptive ranks, e.g. high, moderate and low. In the second approach, the risk is estimated based on semi-quantitative vulnerability indicators using numerical thresholds (ranking) and quantitative estimates of the frequency of the natural hazard (e.g. Petrucci and Gulla 2010; Eidsvig et al. 2017). The concept of the quantitative risk analysis (QRA), which quantifies the probability of a given level of loss and the associated uncertainties, has also been touched by Eurocodes (EN1991-17, 2006). Thus, QRA quantifies the risk in an objective and reproducible manner, providing a robust basis for the prioritisation of mitigation actions, efficient risk management for stakeholders and owners, and prediction of losses for the insurance industry (Corominas et al. 2014); recent examples of such QRA approaches to debris flow risk on a road network, in this case relating to the probability of fatalities amongst road users, are given by Wong and Winter (2018) and Winter (2018). Based on the above, it is clear that predictions of losses and associated impacts on the asset, e.g. bridge, tunnel, and in extension at the network level, as in for example highways, are realistic only if the vulnerability is estimated based on advanced approaches that reliably predict the damageability of the assets. The latter is commonly expressed through vulnerability and/or fragility functions, which are discussed in detail in section 4. Risk analysis is performed for a single component, e.g. a bridge or a road cut, linear features, e.g. part of a highway or a network in regional or national level or areas, e.g. counties (Suh et al. 2011; CEREMA 2014; Jenelius and Mattsson, 2015).

1.3 QRA at a network level

Different approaches have been adopted for the performance assessment of transport infrastructure at the network level and the quantification of the consequences of the disaster events. Different levels of analysis, e.g. connectivity, capacity, integrated loss estimation, have been applied depending on the time frame considered such as emergency phase or economic recovery phase, the scale and type of system, that is urban, regional, and national, the objectives of the analysis and the needs of stakeholders (emergency planning, mitigation or network extension planning, insurance) and the information available. An overview of the modelling techniques on the transport infrastructure system performance in disasters is given by Faturechi and Miller-Hooks (2015). The concepts and measures of different approaches are generally categorized as risk, vulnerability, reliability, robustness, flexibility (also known as adaptability), survivability, and resilience. Performance metrics include the travel time, flow/capacity, accessibility, topological measures, e.g. connectivity, direct and indirect economic losses. These quantitative measures are used in disaster management for the prioritisation of mitigation, preparedness, and adaptive actions. The modelling of possible disasters and associated uncertainties includes specific scenarios, simulation of a wide range of scenarios, use of probability distributions, identification of worst-case performance, or historical scenarios. Mathematical models of system performance are classified as analytical, e.g. risk matrix, event tree analysis, fault tree analysis, analytical hierarchy process, simulation, e.g. through Monte Carlo simulation, or optimisation by deterministic or stochastic models. Khademi et al. (2015) reviewed the methods related to the vulnerability of transport networks due to natural disasters, concluding that accessibility indexes often serve as indicators of network vulnerability. Muriel-Villegas et al. (2016) classified the available approaches for transport network reliability to natural disasters in three main areas, namely connectivity reliability, performance reliability, and vulnerability. An overview of network vulnerability analysis, classified to scenario-specific, strategy-specific, simulation, and mathematical modelling approaches is provided in Murray et al. (2008), while the methods and challenges in modelling and simulation of interconnected infrastructure are discussed by Eusgeld et al. (2011) and Ouyang (2014).

In the case of earthquake hazards, most of the efforts have addressed the direct seismic shaking effects, focusing on bridges, which is the most critical asset (e.g. Miller and Baker 2015). The interactions of the urban road network with the built environment in post-earthquake conditions have been examined by Goretti and Sarli, 2006; Argyroudis et al. 2015; Ertugay et al. 2016; and Zanini et al. 2017, considering the effect of building collapses to the connectivity of the network. The extent of the debris of the collapsed buildings that affects the functionality of the road is estimated through simplified geometric models. The damage estimation using fragility functions has been used in the design of new tunnels and in the implementation of earthquake early warning systems for high-speed railways (Fabozzi et al. 2018).

The effects of multiple hazards on a network level have been studied by Hackl et al. (2018) who proposed and applied a modular approach to couple rainfall, runoff, flood, mudflow, physical damages of bridges and pavements, functional loss, traffic, and restoration modelling. Consequences were monetized into direct and indirect costs, considering restoration interventions, prolongation of travel time, and lost trips. This model has been used by Lam et al. (2018) to conduct a stress test on a road network affected by floods and rainfall-triggered mudflow, using fragility functions and functional capacity loss functions.

1.4 Current policies, strategies and guidelines for assessment of transport infrastructure

The importance of risk assessment is proven by the recent research interest in quantitative risk analysis, which is related to the protection of critical infrastructure assets subjected to natural hazards. This is in line with the current strategies for adapting infrastructure to climate change and natural disasters as reflected in various governmental decisions and documents in Europe, (e.g. Council Directive 2008/114/EC; SWD 2013/137; COE 2011), USA (FHWA 2013) and other countries as for example in UK (e.g. Cabinet Office UK 2011; Highways England 2016) and New Zealand (NIU 2011). These frameworks emphasize that the design and assessment should integrate extreme weather events and climate change induced risks into asset management practices toward more resilient infrastructure. For example, practices for predicting 100-year floods in the design may no longer be valid, while greater extremes and more frequent events should be assumed. Furthermore, transportation systems have several vulnerabilities, which are poorly understood and difficult to quantify (Markolf et al. 2019). These vulnerabilities include direct physical, direct non-physical, related to travellers' behaviour and system operators' decision making, indirect physical, due to physical or geographic interconnections and indirect non-physical, due to cyber or logical interdependencies with other infrastructure. In this regard, a risk-based asset management system should include accurate inventories and mapping of assets, sound maintenance practices, hierarchical prioritisation of critical assets and assessment based on a probability and impact assessment. In this context, results of the assessment will not only support planning prevention, adaptation and mitigation of disruptive events, but will also inform the recovery processes required to maintain functionality immediately following a severe event. Therefore, the adaptation strategies go beyond risk management to a resilience-based management concept that determines how a system can adapt to and recover from shocks, and not just avoiding or mitigating them (Cimellaro et al. 2010; Meyer and Weigel 2011; Schweikert et al. 2014; Mattsson and Jenelius 2015; Espinet et al. 2016).

Risk-based management approaches are widely applied by transport infrastructure owners and stakeholders to prioritise the assets with a higher risk that require more detailed assessments or mitigation measures. These approaches are usually given in the form of guidelines and provisions by national transport departments and governmental organisations. The risk assessment is commonly based on screening methods to calculate a risk score using different criteria and factors that describe the hazard conditions, the vulnerability of the assets and their importance. For example, guidelines to identify and prioritise seismically deficient bridges in the US are provided by FHWA (Buckle et al. 2006). The screening is based on seismic rating methods using indices and expected damage. The indices describe the structural/geotechnical vulnerability, such as connections, bearings, piers, foundation, and soil liquefaction, and the hazard intensity. Rating using expected damage is based on fragility functions and estimation of economic losses for given seismic hazard levels. Prioritisation includes bridge importance, network redundancy, non-seismic deficiencies, remaining useful life, and other socioeconomic issues. Seismic screening and evaluation criteria for retaining structures, engineered slopes and embankments, tunnels, culverts, and pavements are also provided by FHWA (Power et al. 2004). In Europe, the seismic assessment of bridges will be based on the on-going update of Part 3 of Eurocode 8 (EN 1998-3, 2005).

With regard to guidelines for the design and assessment of bridges under hydraulic actions, the ones by Kirby et al. (2015) and BD97/12 (2012) are available in the UK, whilst in the US relevant documents are provided by NCHRP (2010a,b), NCHRP (2011) and FHWA (2012a). Multiple factors are considered to calculate a risk score including the scour history, the characteristics of the bridge structures and the watercourses that they cross. The scour depth is estimated for given design return periods based on closed-form solutions.

Vulnerability and risk of transport assets exposed to extreme weather effects are aggravated by climate change and are assessed on the basis of transportation system sensitivity and exposure to weather effects and adaptive capacity (FHWA 2012b). Vulnerabilities are assessed through a combination of quantitative measures and qualitative judgments, based on impact rating scale scorecards, multi-criteria decision analysis or risk matrix approaches (WSDOT 2011; Yang et al. 2013). Thus, based on the international literature there does not exist a well-established methodology for quantifying the losses of transport infrastructure exposed to weather effects.

Existing national and international landslide guidelines are reviewed and evaluated by Wang et al. (2012). Some of these focus on certain topics and issues, e.g. landslide risk management and zoning, mitigation and remediation, slope design, and others are more generic, e.g. geotechnical assessment, land use planning. A summary of available publications, codes and design practices for earthworks associated with transport infrastructure is provided by Griffiths and Radford (2012).

Resilience-based assessment and management are the new philosophies that are gradually being adopted in practical applications of transport assets and are expected to be incorporated in the next generation of provisions and guidelines (Linkov et al. 2014). In this context, different frameworks and assessment tools have been proposed in the literature, e.g. Bruneau et al. 2003; Hughes and Healy 2014; Ayyub 2014; Dong and Frangopol 2015; Chan and Schofer 2015; Rattanachot et al. 2015; Kiel et al. 2016, among others, while EU projects on this topic have been recently implemented as already presented in the Introduction of this paper.

2 Brief description of the main typologies of transport assets

Important transport assets include bridges, tunnels, culverts, retaining walls, embankments, trenches, slopes and pavements. The secondary assets include information and communication technology (ICT), signalling, lighting, and safety (e.g. fences, barriers) components, and buildings, such as tolls or warehouses. Railway systems also include tracks, electric power and communication systems, stations and workshops. Another distinction of transport assets can be made on the basis of urban and inter-urban networks. Some components, such as embankments, slopes or trenches, are mainly encountered in inter-urban networks. A significant difference is the geographic interdependencies of urban systems with other infrastructure, e.g. buried pipelines or cables underneath or buildings in the proximity of the roads. Moreover, due to the lower redundancy of the network compared to the urban ones, the consequences and indirect losses of natural hazards and weather stressors have significantly different impacts on inter-urban transport infrastructure, whilst urban networks have higher redundancy, yet, greater interdependencies with other interacting networks. For example, closure of a highway tunnel or bridge can potentially cause higher total losses compared to closure of a main urban street, as it is easier to follow alternative routes in the second case. However, there are examples of significant losses in case of failures in urban networks, such as the collapse of the Hansin Expressway during the 1995 Kobe earthquake or the consequences of the flash floods in central European cities in 2013. The focus of this paper is on inter-urban roads, whilst additional literature would be required for urban and strongly interdependent networks.

The variation of *bridge* typologies is greater compared to other transport infrastructure; therefore, the available classification schemes are diverse, particularly focusing on the seismic behaviour of bridges (e.g. Applied Technology Council 1985; NIBS 2004; Hancilar and Taucer 2013). The bridge typologies are commonly based on the number of spans and length, particular design considerations, material, type of pier and abutment and deck continuity. The SYNER-G taxonomy (Hancilar and Taucer 2013) includes the following structural characteristics: material, type of superstructure, type of deck, deck structural system, pier to deck connection, type of pier, number of columns per pier, cross section of pier, spans, type of connection to the abutments, bridge irregularity, skew, foundation type, seismic design level. Due to the peculiarity of the *bridge abutment*, its typology is examined here separately, and its typology is related to the structural type of the bridge, e.g. stub, partial or full height, integral. Other characteristics are the depth and the soil conditions of the foundation and the fill material behind the abutment. The depth is dependent on the surrounding topography and geometry of the abutment, while a critical factor for the backfill material is its degree of compaction.

The basic parameters of the typology of *tunnels* are the construction method (bored or mined, cut-and-cover, immersed), the cross-section shape (circular, rectangular, horseshoe), the depth (surface, shallow, deep), the geological conditions (rock, alluvial) and the supporting system (concrete, masonry, steel, etc.). For example, ALA (2001) classifies tunnels into four categories according to the quality of construction and the ground conditions.

The typology of *retaining walls* is related to the construction, and the most common types are gravity, cantilevered, sheet piling, bored pile and anchored retaining walls. In addition, the soil material, slope angle, and water content are relevant parameters in the typology definition of retaining walls.

The main typology characteristics of *embankments*, *trenches* and *slopes* are the geometrical parameters of the construction, that is, slope angle and height as well as the ground conditions (soil material, water level etc.).

Usually, the transport assets are grouped within classes based on the typology properties, and the vulnerability is calculated for a model that represents the entire class. This approach is applied for the risk analysis of a large portfolio of assets as it would be very time consuming and computationally expensive to calculate asset-specific vulnerability models. However, this approach may not be acceptable for some assets within a class due to inevitable differences and peculiarities of each asset. In addition, significant variabilities exist across different countries and different classes of assets are encountered depending on the classification of the transport system. A diversity of assets is also imposed across different transport networks, such as highways, railways and underground transport systems. Table 2 summarises the main characteristics and typological parameters for the road infrastructure assets in non-urban environments. Urban road infrastructure has additional characteristics that describe their interactions with the built environment, such as the distance from buildings or poles, the cover depth of pipelines.

Table 2. Main parameters of road assets' typology.

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

3 Damage description

The performance levels of an asset are defined through damage thresholds called limit states, which define the boundaries between different damage conditions or damage states. Various damage criteria have been used depending on the typology of the asset and the method used for the fragility analysis. In analytical methods, the damage is measured through engineering demand parameters (EDPs), which represent an observable response parameter of the asset. The number of damage states is variable, e.g. none, minor, moderate, extensive, complete, depending on the type of asset. Damage states are usually correlated to the traffic capacity of the assets. In some cases, the damage is correlated to the replacement, repair and enhancement costs as well as to restoration time and delays due to repairs (NIBS 2004; Werner et al. 2006; Mackie and Stojadinovic 2006; Bradley et al. 2010; Tsionis and Fardis, 2014; D'Ayala et al. 2015). For railway infrastructure assets, the same damage measures are used as in highway assets, but with different thresholds between the damage states.

3.1 Bridges

Bridge damage is related to the response of bridge components, i.e. the deck, the piers and foundation, bearings, abutments and expansion joints (Deng et al. 2016). For piers, the damage measures used in practice are the drift ratio, the curvature, rotation, and displacements. The response of the abutments is usually described based on its displacement, i.e. abutment gap, and rotation, while the damage measure for bearings is its longitudinal and transverse shear deformations and/or displacements and for bridge foundations are the sliding and soil bearing capacity. Damage states have been defined for the specific bridge components and for the whole bridge (Tsionis and Fardis 2014; D'Ayala et al. 2015). Most studies consider bridges as serial systems; hence, their damage states are defined by the most vulnerable components (Nielson and DesRoches 2007; Padgett and DesRoches 2009).

Common failure modes due to hydraulic actions include pier or/and abutment settlement or/and tilting due to loss of support to the foundation or/and hydraulic loading aggravated by debris accumulation, damage to superstructure or deck falling off abutment or pier, scouring or washout of the embankment behind abutment (JBA Trust 2014). In case of river crossings, failure mechanisms of rock bank protections include slope instabilities, sliding, movement of rock cover, migration of sub-layers, etc (Melville and Coleman 2000; CIRIA et al. 2007). Most of these mechanisms are related to flow characteristics, such as discharge, flow velocity, and water levels and also to geotechnical characteristics, such as density of materials or pore water pressure (Roca and Whitehouse 2012).

3.2 Tunnels

Earthquake effects on tunnels include slope instability leading to tunnel collapse, portal failure, roof or wall collapse, invert uplift, spalling, cracking or crushing of the concrete lining, slabbing or spalling of the rock around the opening, bending and buckling of reinforcing bars, pavement cracks, wall deformation, local opening of joints and obstruction at the tunnel portals due to rock falls. Non-seismically induced landslides can cause similar damage modes. Flooding is not considered as a crucial hazard for tunnels; however, underground water can have a damaging effect on the tunnel lining during its lifetime due to corrosion of reinforcement or degradation of concrete strength (ITA 1991).

In terms of fragility assessment, damage states commonly describe the response of the main tunnel components, i.e. liner, portal and support systems. Different damage states and damage measures have been proposed in the literature depending on the method of fragility analysis and the typology of the tunnel. In empirical approaches damage states are defined based on the extent of lining cracks (e.g. NIBS 2004; ALA 2001), while in numerical methods damage states are defined based on the exceedance of lining capacity (Argyroudis and Pitilakis 2012; Argyroudis et al. 2017), number of activated plastic hinges in the liner (Lee et al. 2016), lateral displacement (Huh et al. 2017) or permanent rotations of longitudinal joint (Fabozzi et al. 2017).

3.3 Embankments

Failure modes of embankments subjected to earthquakes are related to ground failures due to soil liquefaction or dynamic loading. Main failure modes include sliding or slumping of the embankment, cracking at the surface and settlement of the embankment. Damage states are defined in the literature based on the extent of settlement or ground offset (NIBS 2004; Werner et al. 2006; JRA 2007; Maruyama et al. 2010; Argyroudis and Kaynia 2015).

The failure mechanisms commonly encountered during flooding involve hydrostatic and hydrodynamic forces that result from overtopping, seepage forces and the lateral pressure caused by headwater elevation. Common failure modes in coastal and riverine environments include overtopping erosion, softening by soil saturation, underseepage, and piping, through seepage (internal erosion) and piping, wave erosion, lateral sliding on foundations, other failure modes including culvert failures and pavement failures (ALA 2005; Briaud and Maddah 2016). Damage states are not provided in the literature; however, the ones proposed in case of earthquake damage can be adopted for floods. The effects of climate change, resulting in excess water, high soil moisture and high temperatures on highway pavements are described by Willway et al. (2008).

3.4 Slopes and Trenches

Earthquake or rainfall-induced landslides and rock falls can cause partial or complete closure of the road or railbed as well as potential structural damage of the pavement or the rail track. Roads and railbeds constructed on slopes are subjected to potential failure mechanisms due to large movements of the slopes or slumping of the sides of the road or railbed. Damage states are defined according to the extent of settlement or ground offset (NIBS 2004; Argyroudis and Kaynia 2015) and in some cases they are correlated to the permanent ground deformation as well as to restoration time and traffic capacity (Winter et al. 2014; Argyroudis and Kaynia 2014; D’Ayala et al. 2015).

3.5 Bridge abutments and Retaining walls

The main form of seismic failure of backfills behind bridge abutments or retaining walls is the backfill settlement or heaving (White et al. 2007). Structural damage of the abutment wall includes permanent dislocation, i.e. sliding, rotations. In addition, pounding of the deck to the abutment can seriously affect the overall response of the bridge due to collision forces. Damage states have been defined (Argyroudis et al. 2013).

4 Fragility analysis methods and intensity measures

4.1 General

The degree to which an asset exposed to a hazard can be damaged is commonly expressed through the *damage functions* that correlate the severity of the hazard with the level of the expected damage. The most common types of damage functions used in QRA and reliability analysis are the fragility and vulnerability functions. Other simplified approaches include indicator-based methodologies, which asses the vulnerability of an asset or system based on a weighted scoring system for ranking and evaluating the critical characteristics of the assets (Kappes et al. 2012).

Fragility functions express physical damage and give the probability that the asset exceeds some undesirable limit state, e.g. serviceability for a given level of environmental excitation, such as force, deformation, or other forms of loading to which the asset is subjected (Figure 1a). In other words, a fragility function expresses the reliability of a structure as a function of a defined dominant stress variable. The excitation or stress variable is commonly related to an engineering demand parameter (EDP), which depends on the type of asset and the hazard that the asset is subjected to (Porter 2015). The fragility functions are usually described by a lognormal probability distribution, as follows (Eq. 1)

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

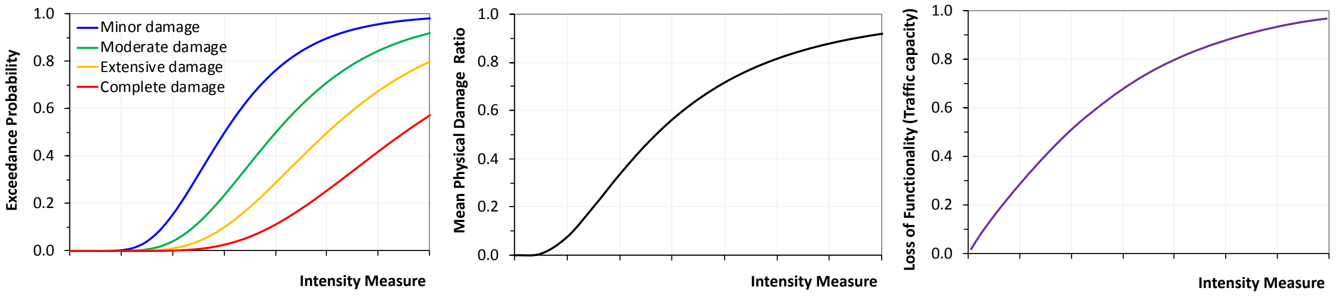
where $P_f()$ is the probability of exceeding a particular limit state, LS, for a given intensity level defined by the intensity measure, IM, e.g. peak ground acceleration-PGA for earthquake or peak flow discharge for flood hazard, Φ is the standard cumulative probability function, IM_{mi} is the median threshold value of the intensity measure, required to cause the i_{th} limit state, and β_{tot} is the total lognormal standard deviation, as per Eq. 2.

Vulnerability functions describe the losses to a given asset or system of assets as a function of environmental actions (Figure 1b). The losses are commonly expressed in terms of damage repair costs, usually normalised by replacement cost, casualties, commonly given as a fraction of the occupants or travellers, or down-time in terms of days or fractions of a year, during which the asset or system is not operating. The vulnerability functions can be generated using the fragility functions by applying consequence analysis that provides uncertain loss conditioned on damage state. Another means for measuring damage is to express the *functionality loss*, such as the reduction of traffic capacity due to a given intensity measure (as per Figure 1c).

Practically, the fragility and vulnerability functions can be derived from empirical, analytical, expert elicitation and hybrid approaches (Pitilakis et al. 2014; Porter 2015; Silva et al. 2019). Analytical approaches validated by experimental data and observations from recent events have become more popular, in particular for earthquake hazard (e.g. Banerjee and Shinozuka 2008; Argyroudis and Pitilakis 2012; Argyroudis and Kaynia 2015), as they are more readily applied to different structure types and geographical regions, where damage records are insufficient. Furthermore, the improvement of computational tools, methods, and skills allow comprehensive parametric studies and better control of the associated uncertainties. The fragility functions express the vulnerability of assets in quantitative terms and can be directly integrated into the QRA. Fragility functions encapsulate the concepts of the factor of safety and reliability index, and they are used to evaluate the reliability of an asset based on a probabilistic approach. In particular, the traditional deterministic approach to define the safety factor of an asset, i.e. ratio between the design strength and the applied load, is not representative due to the inherent uncertainties in strength, loading and modelling assumptions adopted. The reliability index introduces the concepts of uncertainty in capacity and demand but provides information only about reliability relative to a specific design. On the contrary, fragility functions characterise the system reliability over the full range of loads, to which an asset might be exposed, thus, provides a more comprehensive perspective of infrastructural reliability (Schultz et al. 2010). Apart from that, fragility functions have also been proposed to be used in the design process (Mangalathu et al. 2018) as they provide information for the performance of an asset under diverse hazards and as a function of different hazard magnitudes and/or frequency design levels. Thus, they provide means of resilient designs because they specify the likelihood of intermediate damage levels that affect the functionality and restoration of service (Bruneau et al. 2003).

The generation of fragility functions hinges on the definition of representative *intensity measures*, IM, which describe the severity and characteristics of the hazard and are used to correlate the response of each asset with the hazard. The selection and use of specific IM in the fragility analysis is related to the adopted hazard model, the typology of the asset, the considered damage modes and the method of fragility analysis. Optimum IMs are defined based on practicality, effectiveness, efficiency, sufficiency, robustness, and computability (Mackie and Stojadinovic 2005). In the case of earthquake, several measures of the strength of the ground motion have been proposed that describe different properties of the motion. They include peak ground acceleration/velocity/displacement, spectral acceleration/velocity/displacement, Arias intensity, etc. Most common intensity measure types used are the peak ground acceleration (PGA) when ground shaking is the cause of damage and the permanent ground deformation (PGD) when ground failure, e.g. due to liquefaction, fault rupture or slope failure, is the trigger of damage. Representative intensity measures for slow-moving landslides and debris flows are the permanent ground displacement and landslide volume respectively (Corominas et al. 2014; Winter et al. 2014). In the case of floods, the main parameters are the peak flow discharge and velocity, flood height (water depth) and hydrograph defined by discharge as a function of time (Kirby et al. 2015; Lamb et al. 2017; Pregnolato et al. 2017). Scour depth, i.e. at bridge foundation, has been widely used as intensity measure; however, it is recognised that it is a consequence of the flood hazard and doesn’t explicitly represent the source of the hazard or the load to the structure (Yilmaz et al. 2016). In coastal environments, wave parameters, such as run-up elevation and significant wave height are also considered. The rain intensity expressed in mm/day (Jasim and Vahedifard 2017), and the lahar depth (Dagá et al. 2017) have been considered as intensity measures for transport infrastructure exposed to extreme precipitation and lahar flows, respectively.

Recently, a substantial increase in interest in the seismic fragility assessment of transport infrastructure is evident in the literature. The studies concern mainly bridge assets (Tsionis and Fardis 2014; Billah and Alam 2015; Gidaris et al. 2017; Stefanidou and Kappos 2018). The available fragility models for railway and highway infrastructure other than bridges, i.e. tunnels, embankments/cuts, slopes, retaining walls, subjected to seismic shaking are summarized by Argyroudis and Kaynia (2014). With regard to the available fragility models for transport assets exposed to ground failures, these were also found to be limited. Generic fragility functions for tunnels, roads, and bridges subjected to ground failure due to liquefaction and fault displacement are provided by NIBS (2004), yet not accounting for the typology of assets or the soil conditions. The following subsections summarise the available fragility functions for transport assets for different hazards. These fragility models provide measurable means for expressing physical damage, e.g. structural and/or geotechnical failures, of transport assets subjected to multiple hazards. Thus, these fragility models do not refer to the loss of non-structural capacity, e.g. the functionality loss of a road due to icy pavement, unless otherwise stated.



(a) (b) (c)

Figure 1. Examples of fragility functions (a), vulnerability function (b), functionality loss function (c).

4.2 Bridges

Empirical fragility curves for bridges have been developed based on post-earthquake damage observations, such as 1994 Northridge and 1995 Kobe earthquakes, using different statistical approaches (e.g. Basoz and Kiremidjian 1998; Shinozuka et al. 2001). Analytical methods have been widely applied, that include various simulation techniques such as nonlinear static analysis (e.g. Stefanidou and Kappos 2017), nonlinear time history analysis (e.g. Kwon and Elnashai 2010; Avşar et al. 2011), incremental dynamic analysis and Bayesian approaches (e.g. Gardoni et al. 2002).

Soil-structure interaction (SSI) effects on fragility analysis of bridges have been addressed in several studies (e.g. Stefanidou et al. 2017), while liquefaction-sensitive fragility functions were developed based on numerical modelling accounting for SSI effects (Brandenberg et al. 2011; Aygün et al. 2011). The combined effect of flood-induced scouring and earthquake to the fragility of bridges has been studied by Dong et al. (2013), Banerjee and Prasad (2013), Prasad and Banerjee (2013), Kameshwar and Padgett (2014), Guo et al. (2016), Yilmaz et al. (2016, 2017). Gehl and D'Ayala (2016) developed multihazard fragility functions through the use of system reliability methods and Bayesian networks. The influence of deterioration effects, such as corrosion on the seismic fragility has been investigated by Zhong et al. (2012), Choine et al. (2013) and Ghosh and Sood (2016) among others. The effect of retrofitting measures has also been studied (e.g. Padgettt and DesRoches 2009). More recently, Karamlou and Bocchini (2017) proposed a methodology to develop probabilistic functionality-fragility surfaces by integrating fragility and restoration functions. Tanasic et al. (2013) developed analytical fragility functions for multiple span continuous RC bridges considering degradation of the elastic and plastic soil parameters over time due to scour and Kim et al. (2017) obtained flood fragility estimates for a case study bridge, considering multiple failure modes due to scour and corrosion effects to piles and steel reinforcement. Peduto et al. (2018) generated empirical fragility curves for bridge settlement-induced damage in Amsterdam (Holland) using damage surveys and remote sensing measurements of settlements.

4.3 Tunnels

Expert-based fragility models were included in ATC-13 (Applied Technology Council 1985) and HAZUS (NIBS 2004), while empirical fragility curves were proposed by ALA (2001) and Corigliano (2007) based on damage observations in past earthquakes, mainly in Japan and USA. Analytical fragility functions were developed for tunnels and underground structures under seismic shaking (Argyroudis and Pitilakis 2012; Mayoral et al. 2016; Huh et al. 2017; Qiu et al. 2018; Avanaki et al. 2018; Nguyen et al. 2019). These studies considered uncertainties in structural parameters, e.g. tunnel depth, tunnel cross-section, lining thickness, local soil conditions, e.g. strength of soil or rock mass, and ground motion characteristics (use of a range of input motions), which are not captured in the empirical or expert-based models. More recently, the effect of corrosion of the lining has been studied by Argyroudis et al. (2017), whilst Kiani et al. (2016) proposed experimental fragility functions for circular tunnels as a function of fault rupture.

4.4 Embankments

Empirical fragility curves for road embankments have been generated by Maruyama et al. (2010) and Nakamura (2015) as functions of peak ground acceleration (PGA) or peak ground velocity (PGV) based on actual damages observed in Japan. Argyroudis et al. (2013) and Argyroudis and Kaynia (2015) used nonlinear dynamic analyses and developed analytical fragility functions for cantilever bridge abutments-backfill systems and embankments and cuts under seismic shaking. Lagaros et al. (2009) proposed analytical fragility functions for embankments based on pseudo-static slope stability analyses, while Yin et al. (2017) investigated the influence of retaining walls on embankment's seismic fragility following an Incremental Dynamic Analysis. Tsubaki et al. (2016) developed fragility functions for railway embankment fill and track ballast scour based on recorded observations of railway damage in Japan and simulated overtopping water depth. Lozano-

Valcárcel and Obregón (2017) proposed a fragility surface for river levees as a function of the overflow duration and the height difference between the water level and the levee crest (overtopping failure) and the river water level and water level behind the levee (piping failure) based on closed form equations and Monte Carlo simulations. Analytical fragility functions for levees subjected to extreme precipitation as a function of rain intensity for various rain duration and return periods have been developed by Jasim and Vahedifard (2017).

4.5 Slopes

The semi-empirical fragility model provided by Pitilakis et al. (2010) as a function of PGA considers the slope characteristics through the yield coefficient. Wu (2015) developed fragility functions by modelling the combined effects of infiltration and seismic conditions for a combination of slope geometries based on reliability methods. Fragility curves for roads subjected to debris flow were developed by Winter et al. (2014) as a function of the landslide volume based on an expert judgement approach. Martinović et al. (2016) developed generic fragility functions for rainfall-triggered shallow landslides for a range of slope angles in a railway network as a function of rainfall duration.

4.6 Road pavements

Road pavements are constructed along the entire road network and form the surface for traffic, e.g. passenger and goods vehicles. Therefore, they are constructed on and in bridges, embankments, tunnels and other civil works. Available research that studies weather impacts, i.e. rainfall, flooding, snowfall, ice, wind, fog, or temperature, on roads is summarised in Pregnolato et al. (2017). This study was based on observations and data from past events, modelling and simulations or experiments and is focused on particular occurrences or regions. The objective was to examine the effect of weather stressors, such as the rainfall intensity, on traffic conditions, such as the vehicle speed, and not the physical vulnerability, i.e. structural or geotechnical, of the assets in the form of fragility functions. This paper also contains a function that correlates the floodwater depth with the vehicle speed. Additional functional capacity models for high-speed and local roads sections inundation have been suggested by Lam et al. (2018).

4.7 The missing fragility and functionality loss models

It is evident that numerous studies have assessed the physical vulnerability of individual transport assets, such as embankments, tunnels, and mainly bridges exposed to earthquakes. Regarding other hazards, past studies have focused on the effects of liquefaction, landslides, debris-earth flow and flood and the combined effects of scouring and earthquakes. Again, these studies mainly concern bridges, and this is also the case for those investigating the effects of potential mitigation measures, deterioration due to previous hazard events or ageing effects on the fragility of the assets, the majority of which refer to structural or geotechnical damage. Additionally, functionality loss models, which quantify induced, i.e. non-structural related, effects hindering mobility are very limited or completely missing from the literature. Therefore, there is a need to develop well-informed models that correlate the level of functionality, i.e. traffic capacity, with an appropriate hazard metric, e.g. floodwater or snow depth, volume and depth of debris. These include, for example, the closure or partial obstruction due to: i) inundation depth, snow, ice or debris accumulation on the pavement, ii) rockfall, ice or debris on the road surface at bridge decks, iii) debris or water flow and accumulation on the road/embankment surface originating from the slope. Such models can be derived based on the available observational, experimental and modelling analysis, as well as expert elicitations and safety criteria for vehicles.

5 Modelling challenges in the development of analytical fragility functions

5.1 Soil-structure interaction (SSI) effects on transport assets

SSI effects can influence the performance of structures under earthquake shaking or combinations of hazards (Mylonakis and Gazetas 2000). The numerical modelling of the structure and subsoil is commonly performed using numerical methods such as finite difference method, finite element method and boundary element method. According to Bowles (1996) and Dutta and Roy (2002), numerical techniques can incorporate the effects of material nonlinear behaviour, heterogeneous material conditions, stress anisotropy, hysteretic and radiation damping as well as changes in geometry of the supporting soil medium in the dynamic soil-structure interaction analysis. Generally, the selection of the SSI modelling technique significantly affects the vulnerability assessment of an asset (Kwon and Elnashai 2010). The increase in computational power and resources in the last decade resulted in significantly more intensive research efforts using analytical methods and more sophisticated models to enable more accurate assessments of structural components and SSI effects. The approaches found in the literature can be categorised in: (a) models with emphasis on soil-foundation elements and simplified structural components (e.g. Argyroudis et al. 2013), (b) models with emphasis on structural details and simplified soil-foundation elements or methods of analysis (e.g. Nielson and DesRoches 2007; Aygun et al. 2011), (c) computationally complex models with detailed structure and soil-foundation elements and methods of analysis (e.g. Kwon and Elnashai 2010), reflecting an escalation of accuracy on the basis of high fidelity computational models.

Bridge models including SSI effects commonly simulate the deck using linear-elastic elements, while for the piers inelastic beam-column elements are employed. Abutments are modelled with spring elements (linear, multi-linear, non-linear) that simulate the response of the abutment and backfill soil. For seat type abutments, gap elements are added to the model to represent the opening and closure in expansion joints (Mitoulis 2012). The foundation is usually modelled using bilinear (p-y) springs along the length of the piles, representing the non-linear force-deformation relationship of the foundation and soil by the inertial and kinematic SSI effects (Kappos et al. 2012). In more simplified SSI models, linear springs or fixity conditions are adopted for the foundation (e.g. Stefanidou et al. 2017). A full SSI model includes kinematic and inertia interaction, i.e. masses, non-linear stiffness and damping. The modelling may incorporate either two-dimensional (2D), three-dimensional (3D) or combined approaches with simplifications of the structural or soil-foundation elements. For example, a 3D bridge superstructure, 2D soil domain and one-dimensional (1D) lateral coupling p–y, t–z, and q–z springs was developed by Aygun et al. (2011) and Nielson and DesRoches (2007) in OpenSees to produce fragility functions for bridges. The bridge deck and piers are modelled using linear elastic elements in a lumped model comprising a 3D ‘spine’ model of the bridge, which is adequate for the needs of parametric vulnerability analysis. Other researchers employ SDOF models when the bridge can be adequately approximated by an equivalent column and a lumped mass at its top, a simplification that is allowable by the codes in the longitudinal direction of regular bridges (e.g. Anastasopoulos et al. 2015).

The response of the soil-structure coupled system is commonly analysed by 2D FEM for the seismic fragility analysis of *tunnels* (Argyroudis et al. 2017, Argyroudis and Pitilakis 2012), embankments and cuts (Argyroudis and Kaynia 2015) or retaining walls (Argyroudis et al. 2013) using a variety of software platforms, such as ABAQUS, PLAXIS or FLAC. The soil behaviour is typically modelled with the Mohr-Coulomb criterion to account for soil non-linearities. Interface elements are employed to model the interface between the structure, e.g. tunnel, abutment wall, footings, and the soil. In addition, the analyses are usually conducted assuming total stresses and undrained soil conditions, which are most representative during rapid earthquake loading. To account for the accumulation of excess pore water pressures, the definition of case-dependent parameters would be required, such as the water table level or the degree of saturation, leading to increased uncertainty of the SSI simulation. Yet, the effect of the soil saturation is expected to affect the response of the structure and should be considered when studying the effects of flood and scour on the fragility of transport infrastructure (Argyroudis et al. 2018a).

5.2 Treatment of uncertainties

Uncertainties in the analytical fragility modelling are related to:

- the structure and soil parameters, i.e. uncertainty in geometric properties, mechanical and structural parameters, structural modelling, which represent the variability in the capacity of the soil-structure system,
- the hazard parameters, e.g. selection of intensity measure, uncertainty in hazard actions, such as the seismic shaking or the scour depth, which represent the variability in the demand, and,
- definition of thresholds used as damage or limit states (Rossetto et al. 2014; Tsionis and Fardis 2014).

To account for *uncertainties in the capacity* (β_C), sampling approaches, such as the Latin Hypercube or Monte Carlo techniques, are commonly used to generate random combinations of key uncertain and geotechnical parameters (e.g. Guo et al. 2016; Huh et al. 2017; Karamlou and Bocchini 2017; Stefanidou et al. 2017). These parameters include concrete compressive strength, yield strength of reinforcing bars, unit weight of soil, friction angle of soil, among others. For example, based on a sensitivity study for a bridge under the combined effect of earthquake and flood-induced scour, Yilmaz et al. (2017) indicated that the most significant parameters for the performance of the bridge are the compressive strength of concrete, the yield strength of the reinforcing steel, the mass of the bridge, the abutment stiffness and the friction angle of the subsurface soil. Uncertainties in soil unit weight, friction coefficient of sliding bearings and shear modulus of elastomer of bridge isolators are found to have an insignificant impact on the seismic performance of the structure. Depending on the hazard, certain design parameters might become dominant. For instance, Padgett et al. (2013) concluded that the effect of soil properties is important for evaluating bridge damage due to liquefaction. Means for decreasing this type of epistemic uncertainties may be sought in structural health monitoring (SHM) techniques, which may assist in identifying the key properties of the assets, such as the modal and structural parameters of bridges during their lifetime, aiming at updating fragility functions in an effort to represent more realistically the vulnerability of the degraded assets (e.g. Torbol et al. 2013). Based on the study by Stefanidou and Kappos (2017), the uncertainty in capacity for bridge piers under ground shaking varies between 0.14 and 0.50, depending on the limit state and pier type, with an average value equal to 0.35. In case of other assets such as tunnels or embankments, β_C is commonly assigned based on engineering judgment with a representative value being equal to 0.3 (Argyroudis and Kaynia 2015; Qiu et al. 2018). To the best of the authors' knowledge, the uncertainty in the capacity of geotechnical components such as soil embankments has not been investigated before.

The *uncertainty in the demand* (β_D) in case of earthquake hazard, is taken into account by using a suite of ground motions either from real or artificial seismic records scaled to different intensity levels (e.g. Argyroudis et al. 2013; Karamlou and Bocchini 2017). For flood hazards, probabilistic approaches are employed to account for the uncertainty in the hydraulic characteristics, e.g. flood discharge, flow intensity, shape of the flood hydrograph etc, that are associated with the scour depth or water pressure estimation (e.g. Kim et al. 2017; Tubaldi et al. 2017; Yilmaz et al. 2017). Vulnerability assessment of infrastructure, vehicles, and people to landslide hazards involve large uncertainties and complexities; therefore, most of the approaches are based on empirical data and expert judgment (Corominas et al. 2014; Wong and Winter 2018; Winter 2018). The uncertainty in demand is commonly estimated based on the variability in the response of the structure (simulated EDPs) due to the variability of the hazard characteristics, as the lognormal standard deviation about the estimated median in the analysis results (Baker and Cornell 2006; Porter 2015). Therefore, it is dependent on the properties of the structural components as well as the hazard intensity and its characteristics, such as the selection of seismic ground motions. Stefanidou and Kappos (2017) have calculated β_D values between 0.38 and 0.71 for different bridge components and seismic intensities, while in HAZUS methodology (NIBS 2004), an uncertainty factor for seismic demand equal to 0.5 is suggested.

The *uncertainty in limit states and damage thresholds* (β_{LS}) is frequently neglected or is considered directly in the lognormal standard deviation of the fragility function, which is commonly represented by a lognormal cumulative distribution (Argyroudis and Kaynia 2014). In some cases, a Monte Carlo simulation is performed to sample damage thresholds from a uniform distribution in their confidence intervals (Selva et al. 2013). Uncertainties in the definition of limit states for bridge components are discussed by Stefanidou and Kappos (2017), suggesting a uniform value equal to 0.35 for piers, 0.20 for bearings and 0.47 for abutments. A value that is commonly used is 0.4 as per HAZUS (NIBS 2004) recommendations for buildings seismic fragility.

The *total uncertainty* (β_{tot}) is usually introduced in the fragility functions as the summation of the lognormal variances deriving from each component of uncertainty assuming that they are probabilistically independent (Eq. 2).

$$\beta_{tot} = \sqrt{{\beta_C}^2 + {\beta_D}^2 + {\beta_{LS}}^2} \quad \text{Eq. 2}$$

It is realised that different sources of uncertainty are associated with the fragility analysis and achieving an adequate level of modelling fidelity and treatment of uncertainty is a challenge (Silva et al. 2019). The propagation of the various uncertainties and the effect of modelling parameter variation, e.g. material or geometric uncertainty, on the fragility estimates require the assessment of the significance of the modelling parameters on the response of the components within an asset through sensitivity analysis (Padgett and DesRoches 2007). This, on one hand, will facilitate defining the significant parameters and produce more reliable fragility functions, and, on the other hand, will reduce the computational cost for statistical sampling and additional simulations that have insignificant effects on the fragility assessment. The treatment of uncertainties is also related to the scope of the study, for example, when the aim is the fragility analysis of a class of assets, the variation of parameters is larger as opposed to the fragility analysis of a single asset. Notwithstanding this, there is a gap in understanding the significance of a number of parameters in different transport assets exposed to diverse hazards, such as the properties of the soil and structures and the definition of hazard actions.

5.3 Deterioration effects

Numerical models for fragility assessment are usually created to cater for the design needs of the assets, which may neither be accurate nor representative of the current condition of the structure. The time-dependent deterioration effects, which are usually not taken into account, can considerably increase the vulnerability of the assets. Substantial research efforts have been performed on the mechanisms and modelling of the deterioration of structural elements and earthworks. The degradation of structural strength may be attributed to multiple factors, such as corrosion, erosion, other forms of chemical deterioration and fatigue (Melchers and Frangopol, 2008; Andisheh et al. 2016). In particular, the corrosion of steel due to the ingress of chlorides is crucial, and more recent research efforts have focused on the effect of corrosion of reinforcing bars and steel bearings on the seismic fragility (Ghosh and Padgett 2011; Alipour et al. 2011) or reliability (Frangopol et al. 1997) assessment of bridges. The time-dependent deterioration effects on the fragility of other transport assets are limited and further research is required. For example, Argyroudis et al. (2017) showed how the seismic fragility of shallow tunnels is altered when ageing effects due to corrosion are considered following available approaches for over ground structures. The corrosion is commonly modelled by the reduction in the cross-section area of reinforcement as a function of time and the characteristics of the chlorides (e.g. CEBFIB-Task Group 5.6, 2006; Andisheh et al. 2016). In some studies, the reinforcement reduction is estimated using a Monte-Carlo simulation to account for the uncertainty in the factors that affect corrosion (Melchers and Frangopol, 2008; Kallias et al. 2017). It is clear that more reliable deterioration models are needed for the analysis and fragility assessment of corroded RC structures under- and over-ground, including large-scale experimental tests. There is also a need for time-dependent fragility models of deteriorated transport assets subject to hazards other than earthquakes. This includes the change in soil properties, e.g. due to the presence of water, and boundary conditions, e.g. due to scour or erosion, as well as the accumulation of damage, e.g. due to evolving ground movements.

5.4 Modelling of multiple hazards and cascading effects

Hazard interactions and cascading effects can be classified differently, while modelling of multiple hazards is a relatively new endeavour (Ayyub 2014; Gill and Malamud 2014; Zaghi et al. 2016; Liu et al. 2016; Bruneau et al. 2017). The available fragility models that account for hazard interactions at the vulnerability level are limited and mainly focused on bridges. In this section, we provide selected examples to highlight some modelling issues for:

- Uncorrelated hazards of different nature, including for example floods caused by different weather phenomena, flood preceding an earthquake or the opposite. The time between the occurrence of the two hazards, their sequence and their intensities can vary considerably.
- Correlated or cascading hazards, where the secondary hazard is triggered by the primary hazard, including for example, liquefaction, landslide and tsunami triggered by earthquakes, or flood, landslides, extreme wind and debris flow triggered by a hurricane. In this case, the two hazards are concurrent or successive within a short period of time.
- Correlated or uncorrelated hazards of the same nature that may have cumulative effects on the structure, e.g. main-shock and aftershocks, or minor hazard effects occurring before a major stressor over a short or longer period of time. For example, scour holes might be forming at bridge foundations throughout the life of the bridge, of minor or moderate extent, and then followed by an extensive flood that causes extensive scouring, debris accumulation and hydraulic forces on the structure.

The combined effect of uncorrelated hazards such as earthquake and flood-induced scour on the performance of bridges has been researched by Prasad and Banerjee 2013; Banerjee and Prasad 2013; Dong et al. 2013; Guo et al. 2016; Yilmaz et al. 2016. Scour of bridge foundations is a major cause for failure, as deepening of scour around piers and/or abutments during the lifetime of a bridge can coincide with other hazards, such as seismic excitations. Most of the studies consider identical scour depths at all bridge piers associated with specific flood events usually with a return period up to 100-years (e.g. Banerjee and Prasad 2013, Guo et al. 2016) or analysing a range of scour depths, which leads to a large computation effort. The potential flood hazard at bridge sites is commonly not evaluated; however, more recently Yilmaz et al. (2016) assumed a variation of scour depth across multiple piers based on streamflow statistics and regional regression equations. A deterministic scour depth is commonly adopted, while in some cases the uncertainty of scour hazard and its time dependency is considered (Guo et al. 2016). The combined effect of earthquake and flood hazards is represented through fragility surfaces (Yilmaz et al. 2016; Guo et al. 2016), providing the failure probability of the bridge as a function of the corresponding intensity measures, commonly the PGA for earthquake and scour depth or flow discharge for flood. The surfaces are derived based on the fragility functions of each individual hazard, considering the intensity measures as statistically independent random variables. Gehl and D'Ayala (2016) developed fragility surfaces for concrete bridges as a function of PGA and flow discharge based on system reliability methods and Bayesian networks. As expected, scouring increases the probability of damage, however, in some cases it was found there was no further change after a certain scour depth (Prasad and Banerjee 2013). Similar approaches may be applicable for other combinations of hazards, e.g. permanent ground movements preceding dynamic loading, such as earthquakes.

With respect to the modelling of sequences of uncorrelated hazard effects a reasonable approach would be to consider the consequences of the first hazard effects on the structure and subsequently the second hazard effect acting upon the modified and potentially more vulnerable system. In the absence of validated models simulating a sequence of hazards, simplified approaches may be employed. For example, to account for the sequence of flood-induced scour and subsequent earthquake on bridges, the springs that model the resistance of the soil are removed around the piles or shallow foundation down to the scour depth. This is a common approach followed by Dong et al. (2013), Prasad and Banerjee (2013), Banerjee and Prasad (2013), and Guo et al. (2016). However, in this way, the effect of scour geometry and the modification of the soil properties due to saturation and scour is not considered. Tanasic et al. (2013) and Tanasic and Hajdin (2017) estimated the bridge damage probability considering the degradation of soil parameters over time due to scouring using a simplified approach. Bridge failure is the result of either geotechnical or structural failure mechanisms, with the first being the excessive settlement and the second being the failure of the deck (ultimate capacity). At the present time, a comprehensive numerical model that accounts for the scour size and its effect to the soil properties, as well as other hydraulic actions due to flood such as hydraulic forces, and debris accumulation is yet to be reported in the literature.

An example of cascading hazards is the case of seismic excitations and liquefaction effects. Bridge fragility for this case has been studied by Aygun et al. (2011) using dynamic nonlinear p-y elements to model pile-soil interaction along with constitutive models available in OpenSees for liquefiable soils. Also, Brandenberg et al. (2011) developed numerical fragility functions for bridges in liquefied soil as a function of free-field lateral ground displacement by applying a reduction factor in p-y capacity associated with liquefaction.

The cumulative structural damage of transport infrastructure due to cascading hazards of the same nature, such as mainshock-aftershock sequences can be significant. The cascading effects on the seismic fragility of bridges have been studied by Franchin and Pinto (2009), Alessandri et al. (2013), Dong and Frangopol (2015), Ghosh et al. (2015), Kumar and Gardoni (2014). The structural model is commonly subjected to mainshock-aftershock sequences, a challenging issue is the selection of aftershock ground motions that are consistent with the mainshock. One approach is to adopt the same set of records used to represent the mainshock for the aftershocks (Franchin and Pinto 2009; Alessandri et al. 2013). Another approach is to develop probabilistic models to predict the effects of past earthquakes on the structural properties and to assess the effects of degradation on the seismic vulnerability (Kumar and Gardoni 2014). There is a number of other hazard effects of the same nature that cause cumulative effects and thus increase the vulnerability of the structure, which has not yet been researched, such as the fragility of SoA for cumulative flood-induced scour or evolving ground movements.

6 A new methodology for vulnerability assessment of transport infrastructure to multiple hazards

6.1 Transport Infrastructure System of Assets (SoA) in diverse ecosystems

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.

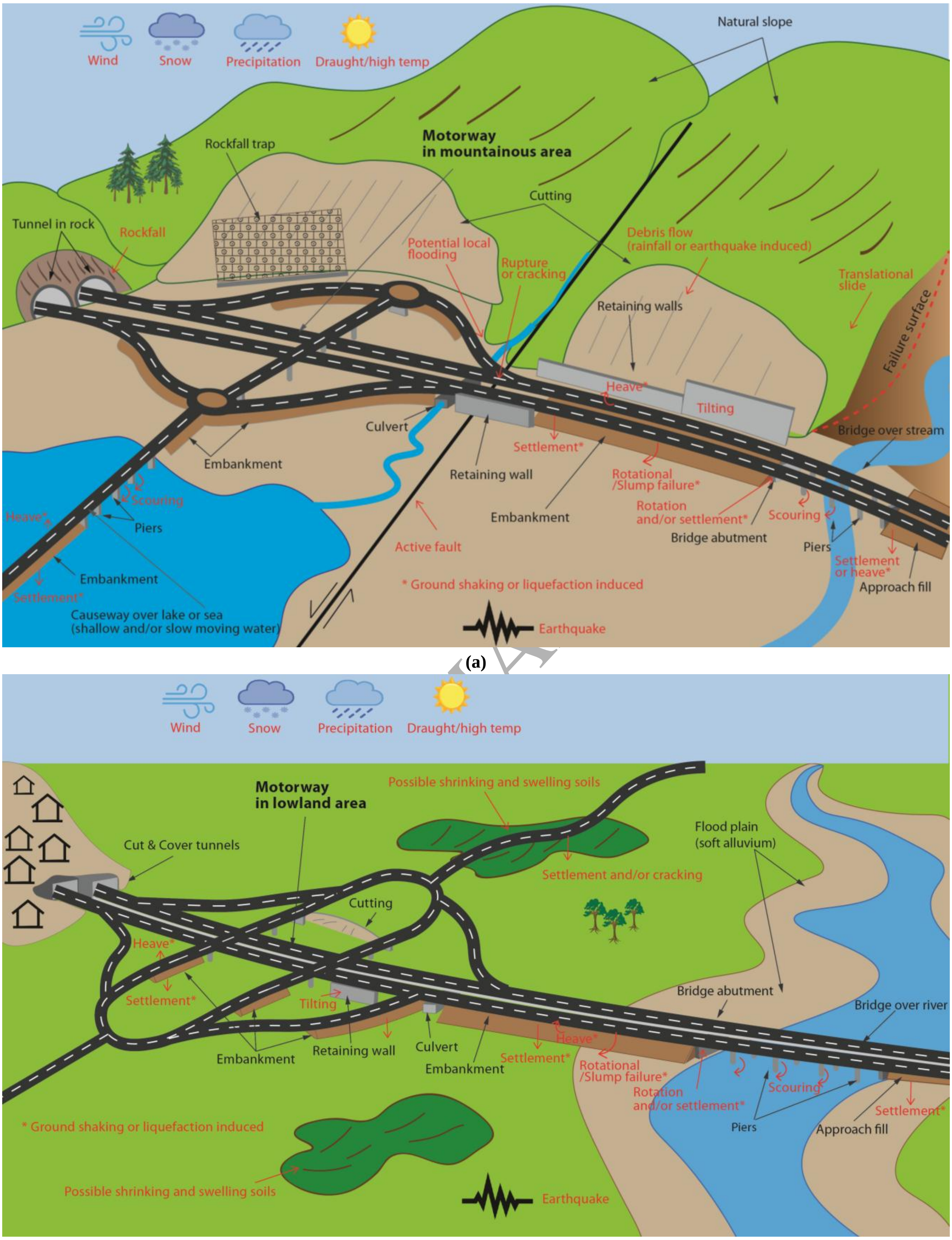
Herein, the newly introduced concept of the transport infrastructure SoA in ecosystems refers to inter-urban roads and illustrate the different elements that comprise the system and the geotechnical and climatic hazards to which the system is subjected. In this respect, the infrastructure is classified 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.

This classification covers the majority of the existing inter-urban road networks, exposed to potential hazards, such as earthquakes, floods, landslides including slides, debris flow and rock fall, extreme temperatures and shrink/swell phenomena. Figure 2 and Figure 3 display sketches of this concept. The transport infrastructure ecosystem approach provides the basis for realising the need for an integrated assessment of the fragility of SoA, as opposed to the examination of the individual assets independently.

The landforms, geomorphological processes, and surface geology are different in mountainous and lowland areas leading to different hazard actions. Stiff soil and rock formations are more common in mountainous areas, while softer alluvial deposits and sediments are predominantly met in lowland areas and valleys. Earthquake or rainfall triggered landslides (slides, rockfalls, debris flows) are common in hilly and mountainous areas. Also, the dynamics of riverine flooding vary with terrain. Floods may manifest within minutes after a heavy rain with fast-flowing of water due to steeper slopes leading to erosion, washout of roads and scour of foundations (Figure 2a, Figure 3a). Lowland areas may stay covered with shallow, slow-moving floodwater for days or even weeks, e.g. overbank flooding. As a result, the floodplain is wider and the amount of water is greater, causing scour of foundations, softening by soil saturation and so on (Figure 2b, Figure 3b).

Moreover, the typology of transport infrastructure varies due to geomorphological conditions, for example, rock tunnels are common in mountainous areas (Figure 2a) and cut & cover tunnels in lowland or urban areas (Figure 3a). Foundations of bridges are shallow in rock/stiff ground conditions and deep, i.e. pile supported, in soft soils. Cuttings and embankments are usually of greater height in steeper geomorphological settings compared to those in flatter terrains. The classification of roads affects also the typology and geometry of the infrastructure (see Table 1). Motorways for high-speed traffic require grade-separated interchanges (Figure 2a, Figure 2b), while lower speed single carriageways typically have at-grade junctions without median strip to separate opposing flows (Figure 3a, Figure 3b).



(a)

(b)

Figure 2. Transport infrastructure in diverse ecosystems exposed to multiple hazards: High capacity and speed roads (e.g. motorways) in (a) mountainous areas, (b) lowland areas

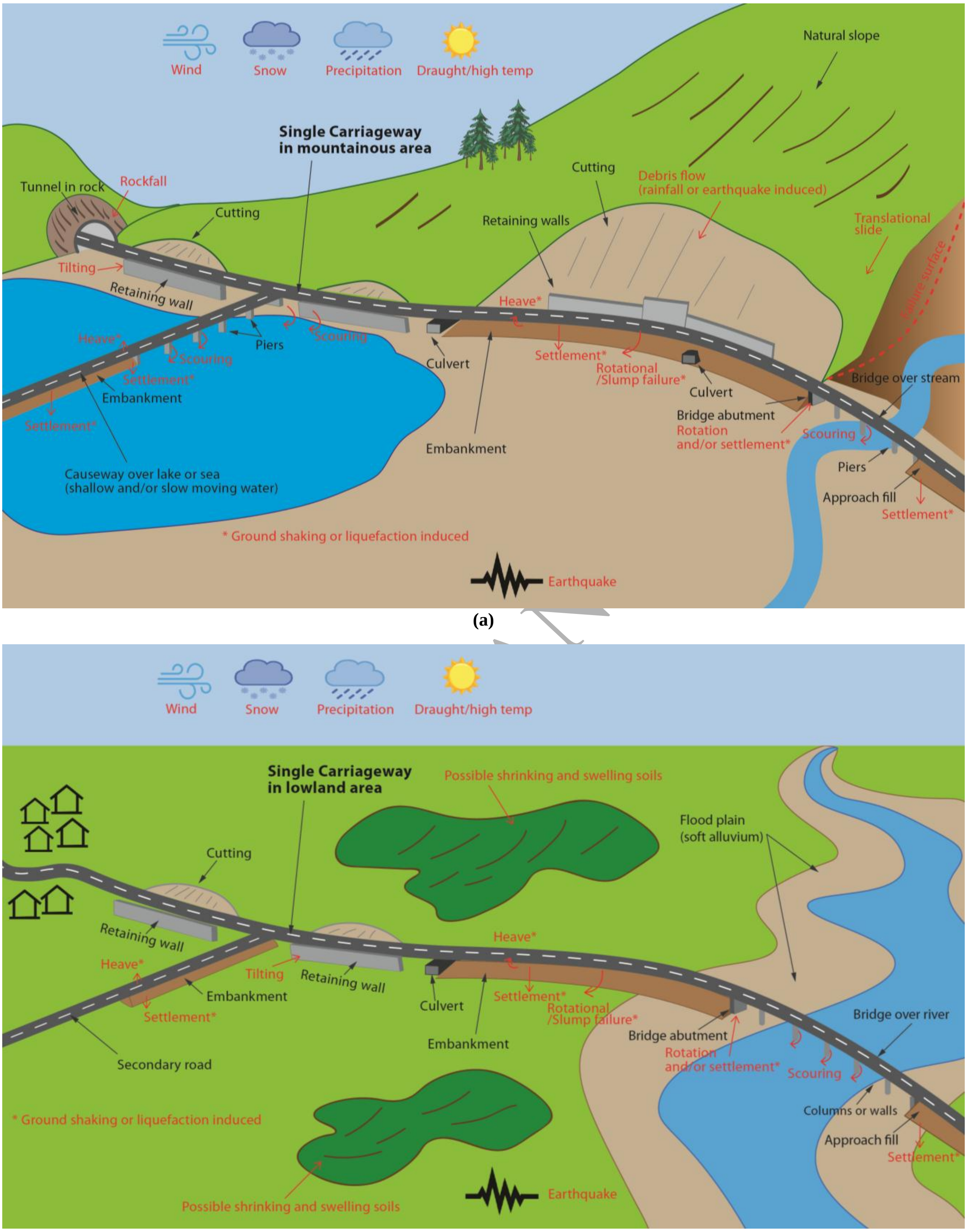
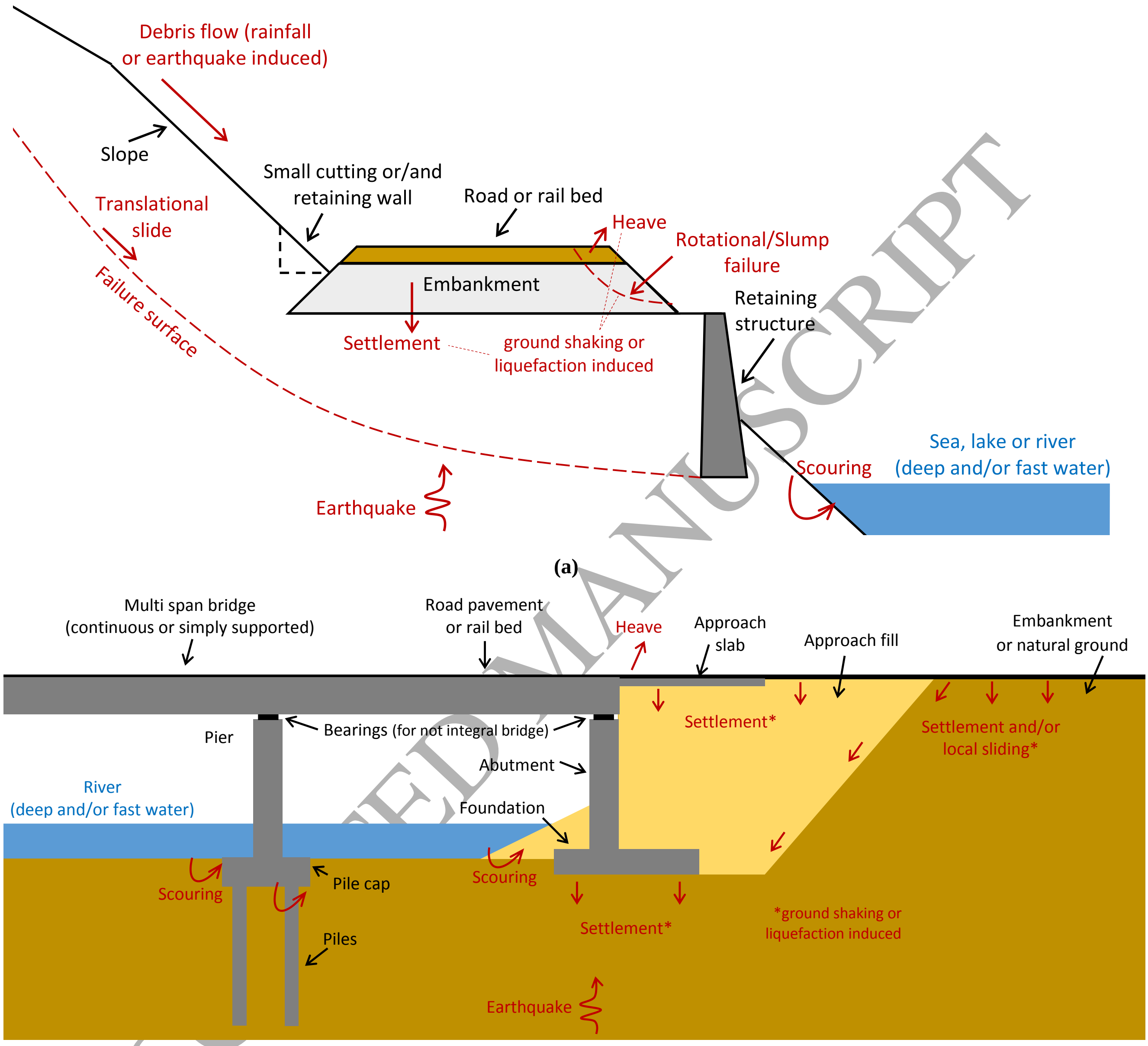


Figure 3. Transport infrastructure in diverse ecosystems exposed to multiple hazards: Lower capacity and speed roads (e.g. single carriageways) in (a) mountainous areas, (b) lowland areas

To highlight the complexity of transportation SoA and the effects due to diverse hazards Figure 4 illustrates two typical sections that can be encountered in either of the ecosystems illustrated in Figures 2 and 3. The first is a transverse and the second one is a longitudinal section.



(a)

(b)

Figure 4. Multiple hazard effects on representative transport System of Assets (SoA): (a) embankment, slope, retaining structure, (b) bridge, abutment, foundations, backfill.

The SoA illustrated along with common hazard effects in Figure 4a includes slopes responding together and interacting with a road pavement or railway tracks on embankments and supported by retaining structures, 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 (FHWA 2014; FHWA 2015).

With reference to Figure 4b, 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 (Power et al. 2004; Buckle et al. 2006).

6.2 Methodology for the development of numerical fragility functions for transport SoA exposed to multiple hazards

The proposed methodology is described in the following six steps and illustrated in a flowchart (Figure 5). This approach is practically applicable for evaluating the physical damage, i.e. structural or geotechnical, and not for the loss of functionality, as discussed in section 4.7.

(i) Definition of the basic configurations of the SoA, including geometry and material of the assets and the components and properties of the soil. The properties are strongly dependent on the local geomorphology and typology of structures and can be selected on the basis of representative assets (see Table 2) considering their variation. A common approach is to consider typical soil profiles on the basis of common engineering practice and code specific classification, for example the Uniform Building Code (UBC) or Eurocode 8 (EC8) use the shear wave velocity ($V_{S,30}$) to classify the soil types (Argyroudis et al. 2013, Argyroudis and Kaynia 2015). Depending on the hazard, the initial soil properties may be altered (for example the strength characteristics can be reduced due to saturation, Argyroudis et al. 2018a), while the shear modulus and viscous damping could change in accordance with the increase in shear strain levels during seismic excitation (Argyroudis et al. 2013, 2017). A sampling technique may be applied by considering the main soil and asset material and geometric properties as random variables to generate a series of SoA samples. The uncertainty in capacity, β_C, can be quantified based on the distribution of the above variables or 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 (see section 3). With reference to Figure 4b, the EDPs for bridge components can include the curvature of the piers, the gap between the deck and the approach slab at the abutments-width of the expansion joint, displacement of the bearings and maximum moment on the deck, while the EDP for the backfill can be described by the permanent ground displacement. Relevant limit states and thresholds for corresponding damage states (e.g. minor, moderate, extensive, complete) are given in the literature or can be defined by sectional analysis based on which the capacity of the deck or pier can be defined. The uncertainty in limit states, β_{LS}, is usually estimated on the basis of expert judgment.

(iii) Definition of hazard actions and intensity measures (see also section 4), which depends on the type of assets and scope of the analysis, including the envisaged accuracy and the number of assets that are under examination. For example, for seismic hazard action and when a time history or incremental dynamic analysis is chosen to be performed, a suite of strong ground motions should be selected for different intensity levels. The latter can either cover a range of possible intensities, e.g. PGA from 0.1 to 1.0g at bedrock, or can be correlated to annual exceedance probabilities of seismic events, having various intensity levels through regional seismic hazard curves. A common approach for the selection of earthquake records is spectral matching, using the target spectrum provided by the codes (Argyroudis and Kaynia 2013; Katsanos and

Sextos 2013). A suite of 7 to 10 motions is usually selected from available databases of earthquake records to cover different frequency contents, duration or seismotectonic conditions (Iervolino et al. 2011). The approach differs when a quasi-static analysis is adopted as for example for underground structures. In this case, the induced seismic ground deformations are applied to the soil-structure model (Argyroudis and Pitilakis 2012; Huh et al. 2017).

For other hazards such as floods, the related actions include scour, debris accumulation and hydraulic forces and these can be calculated based on simplified approaches given by closed-formed solutions and guidelines (e.g. FHWA 2012a; BD97/12, 2012) or well-informed hydraulic models. Again, the IMs, such as the peak water discharge, are correlated with the annual exceedance probabilities of particular flood events through regional flood curves or can cover a range of possible intensity levels (Yilmaz et al. 2016). For structures of great length, such as bridges, the actions by the hazard can be taken as identical along the structure, e.g. at all bridge piers, or temporal and/or spatial variability may be considered on the basis of local effects, e.g. Sextos and Kappos (2008) for earthquake loads, and Yilmaz et al. (2016) for scour effects on piers. Combination of hazards may include a set of subsequent natural actions that are more or less obvious, as for example the sequence of a flood followed by an earthquake, or earthquake excitation and subsequent flood due to tsunami; ground movement and earthquake or the opposite, and finally, two subsequent hazard events of the same nature, for instance main earthquake and aftershock or two floods in a short time frame. The selection and combinations of hazards and their intensity should be decided by the engineer in consultation with experts in other relevant fields as appropriate and in agreement with the stakeholder or owner upon temporal and spatial characteristics and local effects (Marzocchi et al. 2009; Liu et al. 2016).

(iv) 2D or 3D numerical models are 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). Potential key challenges may include the simulation of soil-structure interaction that can be described by elastic or inelastic models considering kinematic and inertial interaction, through equivalent springs or as a continuum layered model, the type of analysis, e.g. non-linear static, incremental dynamic, time history, as well as the definition of boundary conditions and interfaces between the structure components and surrounding soil (see also section 5 for modelling issues). The results of the numerical analyses provide 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 is then used. The uncertainty in demand, β_D, is calculated based on the dispersion of the logarithms of IM-EDP simulated data with respect to the regression fit.

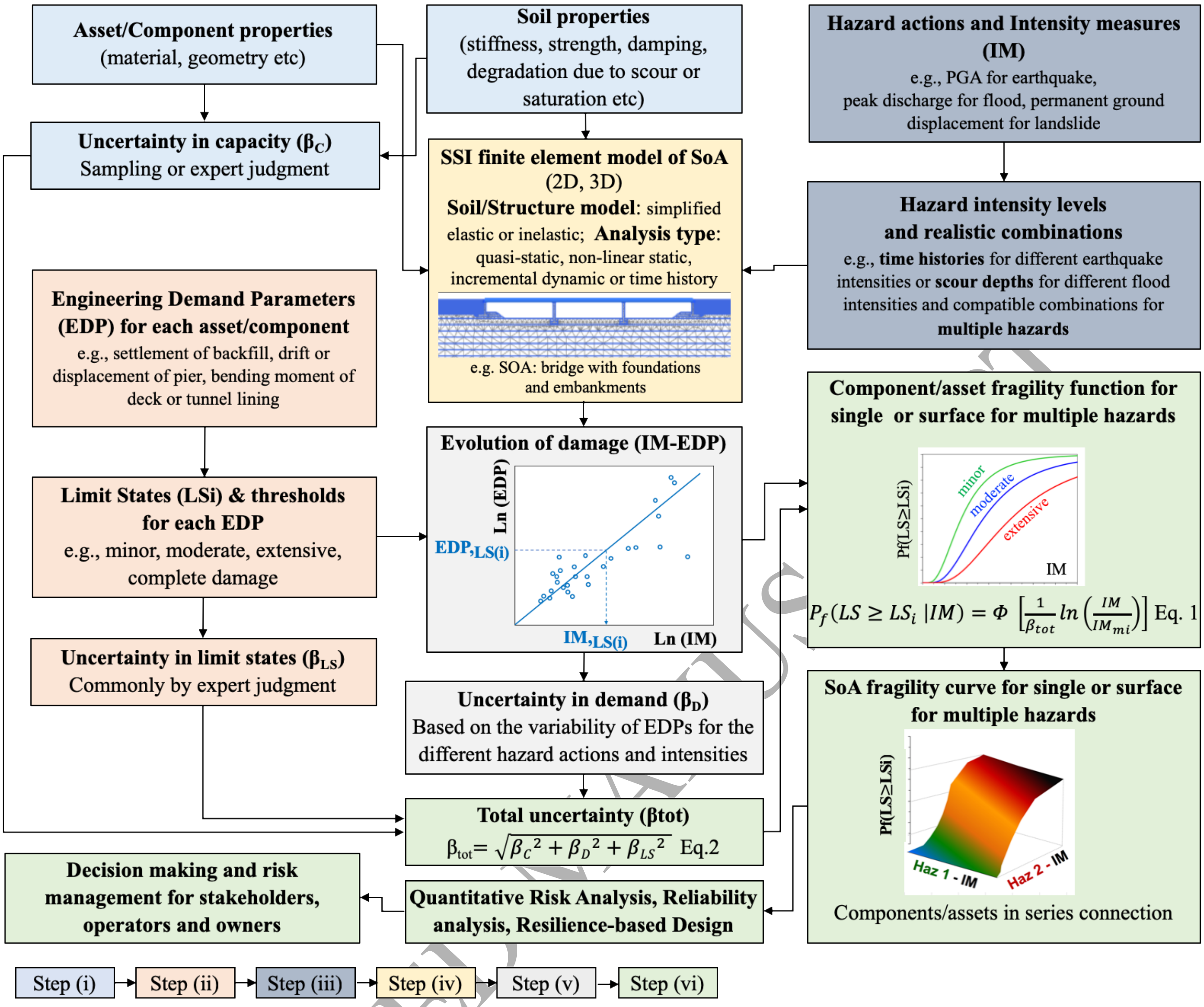


Figure 5. Flowchart for multiple hazard fragility functions of transport systems of assets

(vi) Generation of component, asset and SoA fragility curves and surfaces for single and multiple hazards correspondingly. Each fragility function requires the definition of two parameters (see Equation 1, section 4): 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 is 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 Equation 2, section 5.2). 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) (Cornell et al. 2002). Another approach for the estimation of the fragility parameters based on the IM-EDP pairs is the maximum likelihood method (Shinozuka et al. 2001; Selva et al. 2013). The fragility of the asset (e.g. bridge) or SoA, e.g. bridge, foundations, backfill, can be calculated based on the fragilities of the components or assets respectively, assuming a series connection (Padgett and DesRoches 2009; Stefanidou and Kappos 2017). The combined effect of two hazards can be visualised through fragility surfaces, where the intensity measures are plotted along the two horizontal axes and the damage probability is indicated by the surface. In this case, the IMs, are considered as statistically independent random variables and their joint cumulative probability distribution provides the failure probability under the multi-hazard scenario (Yilmaz et al. 2016). It is noted that it is essential to indicate the order of hazards as the fragility of the SoA is strongly dependent on the sequence of events. These fragility models will enable risk and resilience-based assessments and designs of SoA as well as their reliability and safety characterisation, to facilitate consultants and owners, and to enhance decision-making and risk management delivered by stakeholders.

6.3 Case study

The methodology described in the previous section is briefly discussed herein for a representative SoA exposed to combined effects of foundation scouring due to flooding followed by seismic excitation. This example aims at illustrating succinctly the subsequent steps of the proposed methodology. Yet, the application of the methodology will be included in a future publication, due to the length limitations of this paper.

Step (i) Definition of the SoA and its properties: A three-span pre-stressed integral bridge with its components, i.e. deck, abutment, piers and foundations, together with the backfill and the foundation soil (ground type B, EN 1998-3, 2005) is defined. The properties of the saturated soil layers are modified due to flooding conditions (Argyroudis et al. 2018a). The stiffness and damping soil properties are dependent to the shear strain level during the earthquake (Argyroudis and Kaynia 2014).

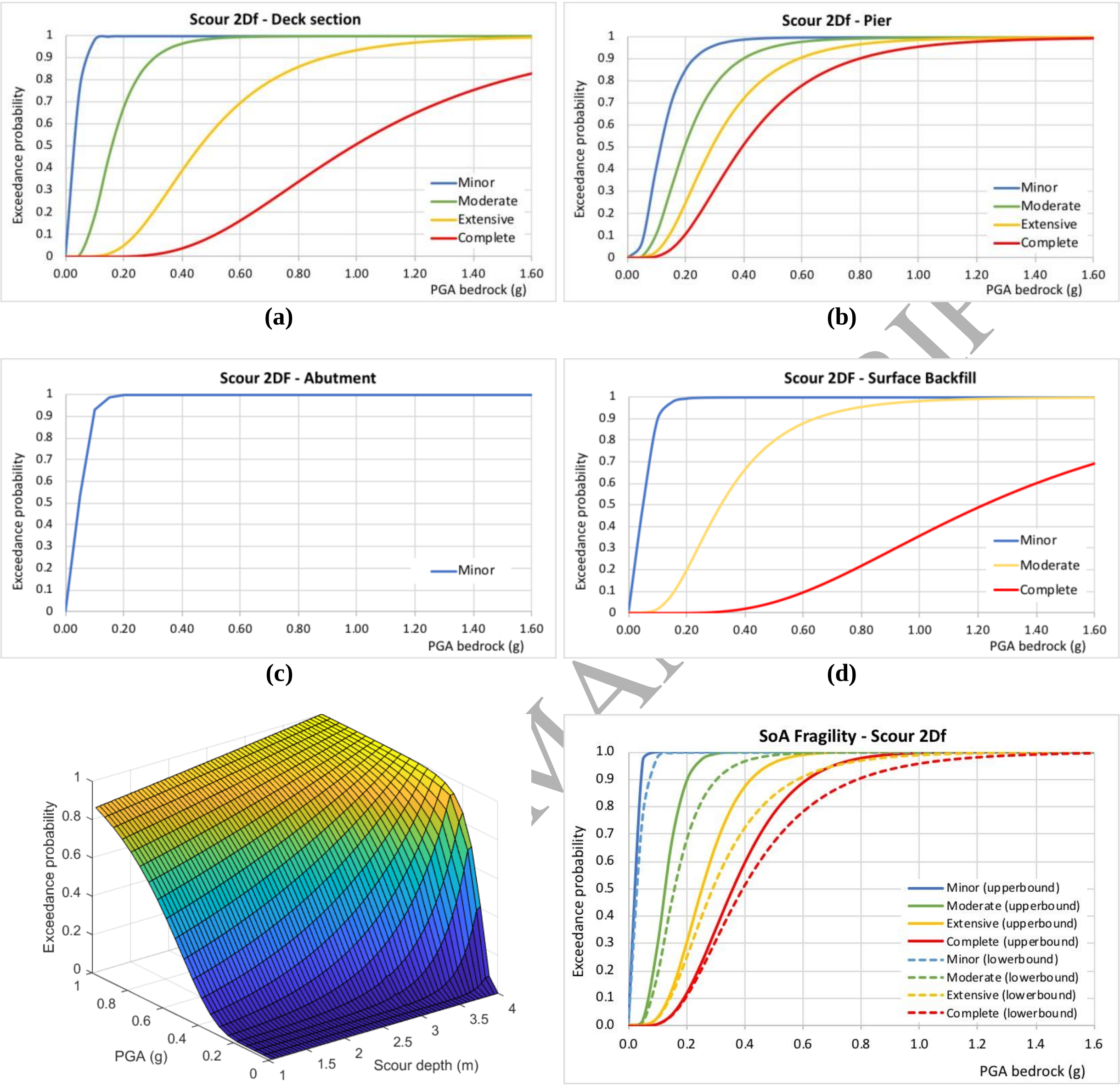
Step (ii) Selection of EDPs and definition of damage states: the maximum bending moment (M_{max}) for critical sections of the deck, pier and abutment and the maximum permanent ground deformation (U_y) of the backfill behind the abutment. Damage states are defined based on the exceedance of the yielding bending moment of the bridge components, and the variation of U_y for the backfill.

Step (iii) Definition of hazard actions: A progressing scour depth at the right abutment is analysed corresponding to $1.0D_f$, $1.5D_f$ and $2.0D_f$, where D_f=2.0 m is the foundation depth. Five real acceleration time histories from earthquakes recorded on rock or very stiff soil were selected as outcrop motion for the analyses scaled to PGA =0.2, 0.4 and 0.6g. The seismic excitations are applied separately for each scour depth in order to simulate the combination of the two hazards.

Step (iv) Numerical model: A 2D FEM was developed in PLAXIS ver.2017 (Argyroudis et al. 2018b). All analyses included initial stages simulating both the initial geostatic stresses and the construction of the bridge. An elasto-plastic soil behaviour was assumed (i.e. Mohr-Coulomb criterion), while the bridge components followed a linear-elastic behaviour. The scouring effect was modelled by gradually removing soil elements around and under the foundation reaching the maximum scour depth, while the seismic input was uniformly applied at the basis of the model.

Step (v) Evolution of damage: For each component of the SoA and each scour scenario, the EDPs are plotted versus the PGA in a logarithmic scale and a regression curve is fitted.

Step (vi) Multiple hazard fragility functions: The fragility parameters are defined and the fragility curves/surfaces for each component are generated. The median PGA is obtained for each damage state using the regression models and the definitions of damage states (step ii). The total variability (β_{tot}) includes three sources of uncertainty. The one associated with the definition of damage states (β_{ds}) was taken 0.4, while the uncertainty due to the capacity (β_C) was taken 0.3. The third uncertainty is associated with the seismic demand and was calculated by the dispersion in response due to the variability of the seismic input motion. Examples of component fragility functions are shown in Figures 6a, 6b, 6c, 6d for the scenario of scour depth equal to $2D_f$. It is seen that the vulnerability of the components may be very different for given scour conditions and seismic excitations. The fragility of the SoA is then extracted assuming a series connection between components and defining an upper and lower bound (Figure 6e). The estimated system fragility can be considerably increased for different scour conditions, for example for a PGA of 0.4g the probability of exceeding moderate and complete damage (lower bound) is increased from 0.51 to 0.97 and from 0.05 to 0.51, when the scour depth increases from $1.5D_f$ to $2D_f$, indicating the importance of the deterioration of the system prior to the seismic action, signifying the importance of the quantification of risk for multiple hazards. The combined effect of the two hazards can also be visualised through fragility surfaces as it is shown in Figure 6f for the case of the bridge pier, i.e. component level, as well as for the entire asset, i.e. bridge, and potentially the entire network, e.g. part of the road network.



(a) (b)

(c) (d)

(e) (f)

Figure 6. Example of multiple hazard fragility functions for a representative System of Assets (SoA) 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 ($2D_f$) and earthquake excitations.

7 Summary and recommendations for future developments

This paper provides a comprehensive state-of-the-art review of natural, geotechnical and weather hazards on transport infrastructure, including the main failure modes, EDPs, and typologies for roads, bridges, tunnels, embankments, retaining walls and backfills. This information is relevant to the vulnerability assessment of the aforementioned assets when subjected to multiple hazards, which is part of the quantitative risk analysis of transport networks. A comprehensive review of the available fragility models for the above assets exposed to multiple hazards was conducted and combinations of hazards, such as earthquakes, floods, liquefaction or landslides among others were examined. Subsequently, the main modelling challenges for the generation of analytical fragility functions, including soil-structure-interaction, deterioration and multiple hazard effects as well as the treatment of uncertainties were discussed. It is recognised that transport assets exist in systems, therefore the concept of System of Assets (SoA) in diverse ecosystems is introduced and classified infrastructure based on (i) the road capacity and speed limits and (ii) the geomorphological and topographical conditions. In this context, a methodological framework for the development of numerical fragility functions of SoA under multiple hazards was also presented. The information provided in this paper can facilitate the quantitative risk analysis of transport assets and the development of new analytical fragility models. Furthermore, fragility functions are essential components in the reliability analysis of transport systems, as they provide a probabilistic characterisation of system reliability over the full range of loads to which a system might be exposed considering the associated uncertainties in structural capacity and demand.

The literature review with respect to the fragility of assets revealed that the majority of the studies focus on either individual transport assets or entire networks, typically considering only one hazard at a time. These studies shed light mainly on the vulnerability of bridges, and secondarily that of tunnels, and the main emphasis had been placed on the ground shaking due to earthquake excitations. Very limited research has been conducted for other assets such as embankments, slopes, retaining walls and abutments. The existing models for these assets are based on empirical data or expert judgment mainly for the earthquake hazard, while they cover limited typologies. Detailed numerical models are rarely used due to a large number of assets and hazards, while simplifications and assumptions are considered along with categorisation of the assets in groups on the basis of similarities in terms of their engineering characteristics, as a means to reduce the computational time. Hence, future research should focus on the improvement of the available models for all assets and for a broader range of typologies and hazards including landslides, earthquakes, flooding, sea level rise and weather stresses. Emphasis should be given to the implementation of more advanced numerical modelling to address SSI and other aspects, such as soil behaviour when subject to multiple hazards. Another challenge is the determination of the optimum IM for each asset and hazard, and the quantification of the uncertainty in capacity and limit state definition, especially where variability in soil, structural material, and local hazard potential, e.g. scour or liquefaction, are jointly present.

Furthermore, research on multiple hazards, such as scouring due to flooding following a strong earthquake or cascading hazards, such as mainshock-aftershock sequences, is very limited and focused only on bridges. Most of the approaches applied so far place emphasis on the structural details (e.g. of bridges) and adopt a simplified model for the foundations and soil behaviour. A common approach to account for the effects of scour due to flood is the removal of spring elements around the foundation down to a depth equal to the scour depth. In addition, the failure modes considered for scoured bridges are the same as the ones used in seismic fragility assessment, while other hydraulic actions, such as the accumulation of debris and stream pressures are usually neglected. Nevertheless, a more advanced modelling approach is needed to account for the scour geometry, the alteration of the flooded/scoured soil properties, the hydraulic actions as well as the potential damage modes for a broader range of bridge and other asset typologies. In some cases, reliability methods and Bayesian networks have been applied to assemble the multiple hazard fragility of a system (e.g. bridge) based on the fragilities of its components. This probabilistic approach allows treating hazard interactions of component-specific fragility functions that have been derived based on various techniques. However, the treatment of uncertainties and the assumptions in the definition of failure modes are based on judgment and not on numerical modelling, which can provide a more realistic articulation of the propagation of the damage within the asset.

Moreover, deterioration or improvements that take place during the life of the assets have only been considered in a limited number of fragility models, predominantly for bridges subject to earthquake excitations. Hence, there is a need to investigate the effect of potential structural (e.g. due to corrosion) and soil (e.g. due to saturation or settlement) degradation on fragility models. Also, the effect of mitigation measures (e.g. drainage of structures, use of gabions, rockfall protection and snow barriers, erosion control systems or geogrid soil reinforcement) on the fragility of the different transport assets exposed to diverse hazards should be investigated.

The focus of this paper was on inter-urban transport infrastructure, while future research will encompass fragility models for urban networks exposed to multiple hazards. In the latter case, interdependencies with the built environment should be taken into consideration, e.g. interactions with energy and utility networks or other transport systems. Additionally, validated functionality loss models, which quantify induced effects, i.e. not losses and damages of structural nature, due to diverse hazards impeding the mobility are very scarce in the literature, and this needs urgent attention for improving infrastructural resilience.

In summary, the available risk assessment frameworks typically consider individual assets of the transport infrastructure, exposed to one hazard only and are not evolving with time, i.e. they neglect the temporal variations and changes to, or deterioration of, the asset during its life that lead to the degradation of its performance. Notwithstanding, assets exist within systems of assets (SoA), within diverse ecosystems, exposed to multiple hazards, such as earthquakes, floods, landslides (including slides, debris flow, and rock fall), extreme temperatures and shrink/swell phenomena. The proposed transport infrastructure ecosystem approach put forward by this paper forms the basis for an integrated assessment of the fragility of the SoA, rather than the individual elements, from which it is formed. This approach has the potential to support well-informed, more accurate and comprehensive risk and resilience assessment of the transport network that will contribute toward adaptation, mitigation and recovery planning for multiple hazards.

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