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Transport infrastructure ecosystems and their vulnerability to geohazards

Écosystèmes d'infrastructures de transport et leur vulnérabilité aux géorisques

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ABSTRACT: Transport infrastructure resilience and risk assessment is typically based on the assessment of individual assets rather than the entire system. We introduce the concept of the infrastructure System of Assets (SoA), or ecosystem, referring to non-urban roads, illustrate the individual elements of the system, and the geotechnical and climatic hazards to which it is subject. The infrastructure is classified based on: (i) the road capacity and speed limits and (ii) the geomorphological and topographical conditions. This classification covers the majority of non-urban networks, exposed to hazards such as earthquakes, floods, landslides (including slides, debris flow and rock fall), extreme temperatures and shrink/swell phenomena. This approach forms the basis for an integrated assessment of the fragility of the SoA rather than the individual elements. Numerical fragility curves are introduced, to articulate the vulnerability of the SoA, to various geohazards and a case study is presented for a bridge exposed to multiple hazards. This framework can contribute to future developments in the resilience management of the transportation network in respect of geotechnical and climatic hazards.

RÉSUMÉ: L'évaluation de la résilience des infrastructures de transport et des risques repose généralement sur l'évaluation d'actifs individuels plutôt que sur l'ensemble du système. Nous introduisons le concept de système d'infrastructure (SoA), ou écosystème, faisant référence aux routes non urbaines, illustrons les différents éléments du système, ainsi que les risques géotechniques et climatiques auxquels il est exposé. L'infrastructure est classée selon: (i) la capacité de la route et les limites de vitesse et (ii) les conditions géomorphologiques et topographiques. Cette classification couvre la majorité des réseaux non urbains exposés à des risques tels que tremblements de terre, inondations, glissements de terrain (y compris les glissements de terrain, les débris et les chutes de pierres), les températures extrêmes et les phénomènes de contraction / gonflement. Cette approche constitue la base d'une évaluation intégrée de la fragilité du SoA plutôt que des éléments individuels. Des courbes de fragilité numérique sont introduites pour articuler la vulnérabilité du SOA à différents risques géographiques. Une étude de cas est présentée pour un pont exposé à de multiples dangers. Ce cadre peut contribuer aux développements futurs de la gestion de la résilience du réseau de transport en ce qui concerne les aléas géotechniques et climatiques.

Keywords: fragility curves; QRA; transport infrastructure; numerical modelling; 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 and impact. For example, the heavy 2007 rainfall in the UK affected the road network and the cost was estimated at £60m, while during the 2009 floods in Cumbria, at least 20 bridges were destroyed or damaged, causing £34m of repair and replacement costs and large societal impact (Cumbria County Council, 2010). 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 & Demirel, 2012). 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, representing more than 50% of the failure cases (Cook et al. 2015).

Hazards are events exogenous to the transport network and are characterized by an intensity, and by both spatial and temporal probabilities of occurrence. Multi-hazard design and assessment has been introduced by Bruneau et al. (2017) among others. 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, speed). Network risk analysis includes hazard identification, vulnerability evaluation of the infrastructure exposed to given hazards and risk assessment in terms of economic, functional and social losses.

Risk-based management approaches are widely applied by transport infrastructure owners and stakeholders to prioritise assets with higher risk that require more detailed assessments and potential mitigation measures. These approaches are usually in the form of guidelines and provisions by national transport departments, governmental bodies or 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, as for example the guidelines for bridges exposed to hydraulic (BD97/12, 2012, UK) or seismic (Buckle et al. 2006, USA) actions. Moreover, resilience-based assessment and management philosophies are being adopted and are expected to be incorporated in the next generation of provisions and guidelines. In this context, different frameworks and assessment tools have been proposed (e.g. Bruneau et al. 2003; Dong & Frangopol 2015; Chan & Schofer 2015; Kiel et al. 2016).

Vulnerability is a fundamental component of quantitative risk analysis under any natural or climatic hazard, and its accurate estimation is essential in making reasonable predictions of losses and consequences. The latter is commonly expressed through vulnerability and/or fragility functions, which can be derived from empirical, analytical, expert elicitation and hybrid approaches (Pitilakis et al. 2014). A susbstantial increase in interest in the fragility and resilience analysis of tranport infrastructure subjected to multiple natural hazards is evidenced in the literature (Argyroudis & Kaynia 2014).

In this paper the concept of the infrastructure System of Assets (SoA), or ecosystem, referring to non urban roads is introduced, including the different elements that comprise the system, and the geotechnical and climatic hazards to which it is subject. A methodology for the development of numerical fragility curves is also introduced, to articulate the vulnerability of the SoA to various geohazards and a case study is presented.

2 TRANSPORT INFRASTRUCTURE SYSTEM OF ASSETS (SOA) IN DIVERSE ECOSYSTEMS

The available vulnerability and risk assessment frameworks typically consider individual assets of the transport infrastructure, exposed to one hazard and are static in the sense that they neglect changes of the asset performance during its life (Argyroudis et al. 2018a,b). Additionally, in most cases the available models are simplified and focus on bridges. 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. Also, their performance changes due to deterioration or improvements that take place during their life and depends on the classification and typology characteristics of the infrastructure.

In this context, the newly introduced concept of the transport infrastructure SoA in ecosystems, refers to non-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 and 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).

This classification covers the majority of the existing non-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 1 ilustrates the case of high capacity-high speed roads in mountainous areas. 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 (e.g. streams) leading to erosion, washout of roads and scour of foundations. 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.

Moreover, the typology of transport infrastructure varies due to geomorphological conditions, for example, rock tunnels are common in mountainous areas and cut & cover tunnels in lowland or urban areas. 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. Motorways for high-speed traffic require grade-separated interchanges, while lower speed single carriageways typically have at-grade junctions without a median strip to separate opposing flows.

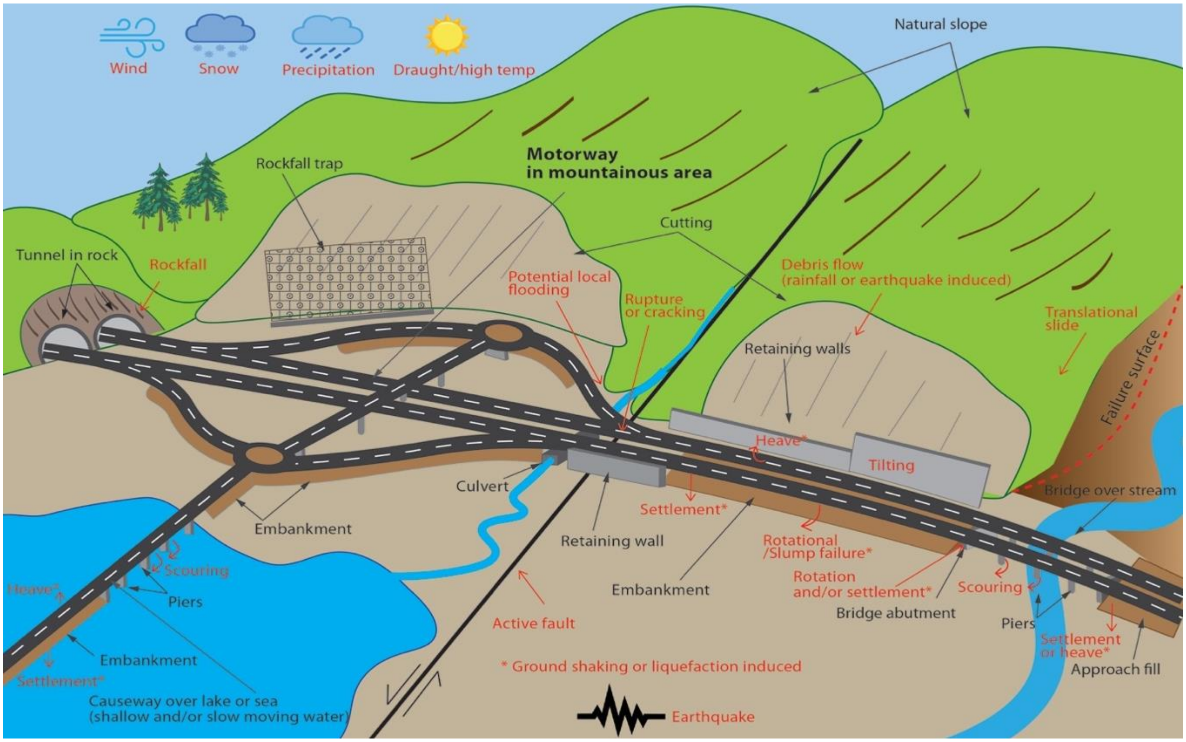


Figure 1. Transport infrastructure in ecosystems: High capacity and speed roads in mountainous areas.

3 NUMERICAL FRAGILITY CURVES FOR SOA

The methodology for the development of numerical fragility curves for transport SoA exposed to multiple hazards includes the following steps.

(i) Definition of the basic configurations of the SoA (i.e. geometry and material of the assets and its components, properties of the soil). Depending on the hazard, the initial soil properties may be altered. For example the strength characteristics can be reduced due to saturation. A sampling technique may be applied considering the main soil and asset material and geometric properties as random variables to generate a series of SoA samples.

(ii) Selection of engineering demand parameters (EDPs) for each asset or component and relevant limit states and thresholds for the definition of damage states. The EDPs for bridge components can include the curvature of the piers, displacement of the bearings and maximum moment on the deck, while the EDP for the backfill can be described by the permanent ground displacement. Definition of limit states and thresholds for the damage states (e.g. minor, moderate, extensive, complete).

(iii) Definition of hazard actions and intensity measures, which depends on the type of assets and the scope of the analysis. 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. For floods, the related actions include scour, debris accumulation and hydraulic forces. Combination of hazards may include a set of subsequent natural actions, such as the sequence of a flood followed by an earthquake, or the opposite, ground movement and earthquake or the opposite, two hazard events of the same nature, i.e. 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.

(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). The numerical analyses provide the required EDP for each component or/and asset.

(v) The results of the analyses conducted in step (iv) in terms of EDPs are plotted versus the IM (e.g. PGA, peak flow discharge) for each asset or component representing the evolution of damage with increasing hazard intensity. A regression model between IM and EDP is used.

(vi) Generation of component, asset and SoA fragility curves for single and multiple hazards based on the results of step (v) and considering the uncertainty in demand (β_D), capacity (β_C) and definition of damage states (β_{ds}) (Argyroudis & Kaynia 2014). 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.

4 CASE STUDY FOR A SYSTEM OF ASSETS – BRIDGE

The methodology described in Section 3 is applied herein for a representative SoA that includes an integral bridge with its components, i.e. deck, abutment, piers and foundations, together with the backfill and the foundation soil. Degradation 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 and the improvement or the compacted state of the backfill or some means of reinforcement. In the present study the combined effects of abutment scouring due to flooding followed by seismic excitation are examined. The corresponding steps are:

i) The bridge considered is a three-span pre-stressed fully integral bridge, with a total length of 100.5 m. Its deck is a box girder with total width of 13.5m. The abutments are 8 m high, the footing is 1 m thick and is 5.5 m long. The piers are wall-type sections (1x4.5 m) 10 m high; the footing is 1 m thickand 3.5 m long. A distributed load of 18.5 kN/m/m is applied to the deck, including the deck self-weight and live loads. The foundation soil is very stiff clay classified as ground type B according to Eurocode 8-Part1, with mechanical properties that gradually increase with the depth. The initial water level was assumed to be at the bottom of the model, while it was gradually increased to 3.0 m above the ground surface (Figure 2). Flooding was accounted for by modifying the properties of the saturated soil layers (Argyroudis et al. 2018a). A calibration procedure was followed to account for the dependency of stiffness and damping on the primary shear strain level during the earthquake (Argyroudis & Kaynia 2014).

ii) The EDPs selected are 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. Yielding of the steel and cracking of the concrete were selected as thresholds for the minor damage state of the bridge deck and pier/abutment respectively. Yielding bending moment (M_y) defines the moderate damage for the deck, while the thresholds for the extensive and complete damage state of the deck correspond to $1.5M_y$ and $2M_y$ respectively. For the pier/abutment the corresponding thresholds are $1.5M_y$, $2.0M_y$, $2.5M_y$. Cracking and yielding moments were calculated for the critical sections using SAP2000. Thresholds for backfill damage are described by Argyroudis & Kaynia (2014).

iii) 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: Kocaeli (Gebze), Turkey, 1999; Parnitha (Kypseli), Greece, 1999; Duzce (Ldeo Station No. C1058 Bv), Turkey, 1999; Umbria Marche (Gubbio-Piana), Italy, 1998; Hector Mine, USA, 1999. In the dynamic analyses (step iv), the time histories are scaled to 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.

iv) A 2D finite element model was developed in PLAXIS ver.2017 (Figure 2). The model width was 400.0 m to reduce the boundary effects on the structure (Argyroudis et al. 2018b). All analyses included initial stages simulating both the initial geostatic stresses and the construction of the bridge. The base of the model was fixed in both horizontal and vertical directions, during the initial and scour steps. For the dynamic analyses the horizontal direction was released and the seismic input was uniformly applied at the basis of the model. For all the analysis phases an elasto-plastic soil behaviour was assumed (i.e. Mohr-Coulomb criterion), while the bridge components followed a linear-elastic behaviour. Interface elements were used to model the interface between the bridge elements and the soil. The scouring effect was modelled by gradually removing soil elements around and under the foundation reaching the maximum scour depth of 4.0m (i.e. $2D_f$) as shown in Figure 3. For each combination of scour and seismic loading, the response of the SoA is estimated.

v) For each component of the SoA and each scour scenario, the EDPs are plotted versus the PGA in a logarithmic scale and a regresssion curve is fitted. An example is shown in Figure 4 for a deck section.

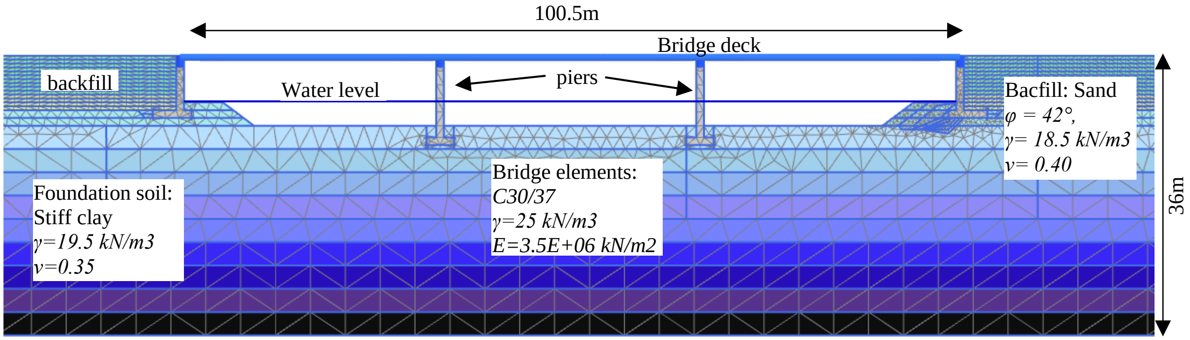


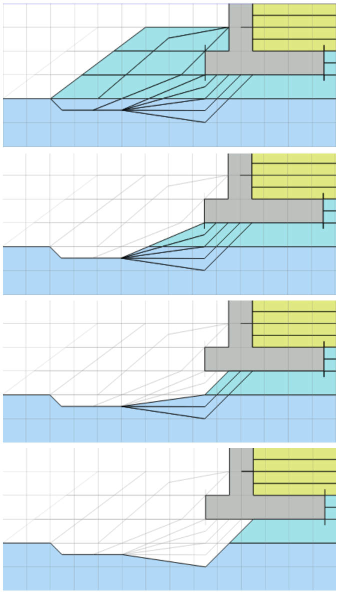
Figure 2. Elevation of the numerical model in PLAXIS 2D.

vi) The fragility parameters are defined and the fragility curves/surfaces for each component are plotted (Figure 5). In particular, the median PGA can be 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. The total variability was estimated assuming that the three contributors are statistically independent and lognormally distributed random variables.

Examples of component fragility curves are shown in Figure 5. It is seen that the vulnerability of the components can vary significantly for given scour conditions and seismic loading. This is important for a more comprehensive assessment of the infrastructure risk and thus for a more efficient management and decision-making around adaptation, mitigation and recovery planning. The fragility of the SoA is generated assuming a series connection between components (Stefanidou and Kappos 2017):

$$\max_{i=1}^{n}[P(F_i)] \le P(F_{system}) \le 1-\prod_{i=1}^{\pi}[1-P(F_i)] \qquad (1)$$

Equation 1 indicates that the probability of the most critical component of the structure exceeding a damage state threshold is less than or equal to the probability of the bridge system exceeding the threshold. Thus, an upper and lower boundary of the fragility curve for the bridge system can be generated. An example is shown in Figure 6.



no scour

scour of 1D_f

scour of 1.5D_f

scour of 2D_f

Figure 3. Senario of scour stages at bridge abutment.

5 CONCLUSIONS

Available risk assessment frameworks typically consider individual transport infrastructure assets, exposed to just one hazard and are not time evolving: i.e. they neglect the changes to, or deterioration of, the asset during its life that lead to the degradation of asset performance.

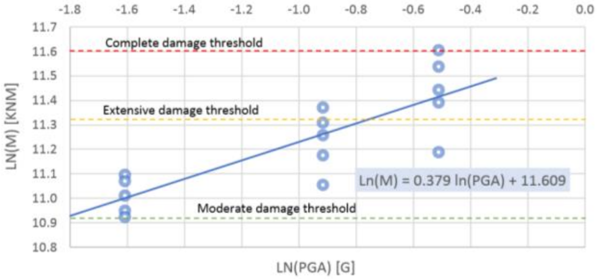
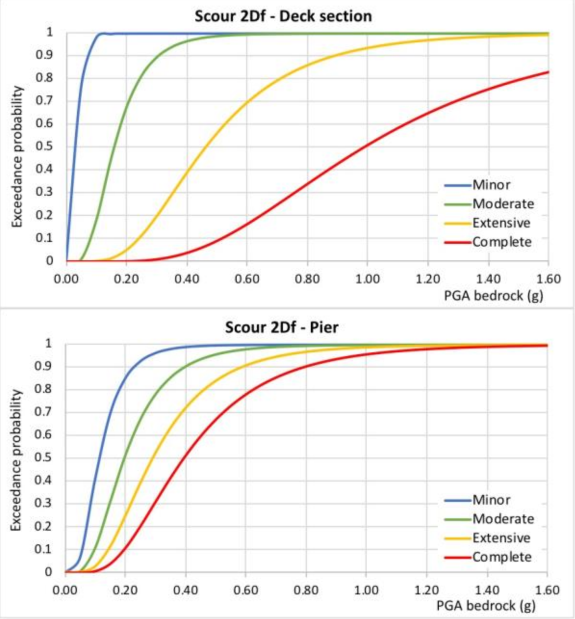


Figure 4. Example of evolution of EDP (bending moment) with intensity measure (PGA bedrock) for scour 2D_f, deck section.



Scour 2Df - Deck section

Scour 2Df - Pier

Figure 5. Examples of component fragility curves (deck and pier) for scour depth 2Df.

Notwithstanding this, assets exist within systems of assets (SoA) in 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 transport infrastructure ecosystem approach 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 towards adaptation, mitigation and recovery planning for multiple hazards.

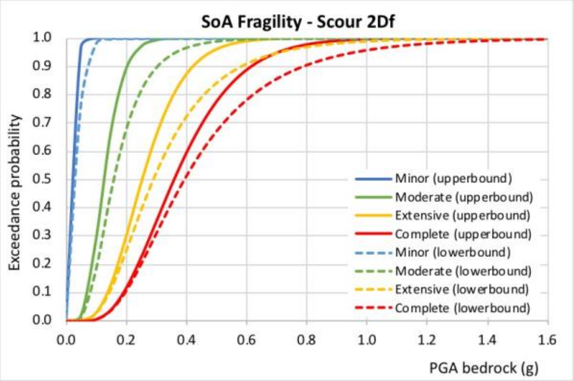


Figure 6. Fragility of the SoA for scour depth 2Df.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Argyroudis, S., Kaynia, A.M. 2014. Fragility functions of highway and railway infrastructure. *Typology definition and fragility functions for physical elements at seismic risk* (Eds. Pitilakis, K et al), Springer.

Argyroudis, S., Mitoulis, S., Winter, M.G., Kaynia, A.M. 2018a. Fragility of critical transportation infrastructure systems subjected to geo-hazards. *Proc. 16th ECEE*, Thessaloniki, Greece.

Argyroudis, S., Mitoulis, S., Kaynia, A.M., Winter, M.G. 2018b. Fragility assessment of transportation infrastructure systems subjected to earthquakes. *Proc. GEESD V*, Geotechnical Special Publication (GSP 292).

BD97/12. 2012. Design manual for roads and bridges: Vol. 3: Highway structures: inspection and maintenance, Section 4: Assessment. The Highways Agency, UK.

Bruneau, M., Barbato, M., Padgett, J., Zaghi, A.E., Mitrani-Reiser, J., Li, Y. 2017. State of the art of multihazard design. *Journal of Structural Engineering* **143**(10), 03117002.

Bruneau, M., et al. 2003. A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra* **19**(4), 733-752.

Buckle, I.G., Friedland, I., Mander, J., Martin, G., Nutt, R., Power, M. 2006. Seismic retrofitting manual for highway structures: Part 1-Bridges, Publication No. FHWA-HRT-06-032, US Dept. of Transportation.

Chan, R., Schofer, J.L. 2015. Measuring transportation system resilience: response of rail transit to weather disruptions. *Natural Hazards Review* **17**(1).

Cook, W., Barr, P.J., Halling, M.W. 2015. Bridge failure rate. *Journal of Performance of Constructed Facilities* **29** (3).

Cumbria County Council. 2010. Cumbria floods November 2009: an impact assessment. http://www.cumbria.gov.uk/eLibrary/Content/Internet/536/671/4674/4026717419.pdf.

Dong, Y., Frangopol, D.M. 2015. Risk and resilience assessment of bridges under mainshock and aftershocks incorporating uncertainties. *Eng. Struct.* **83**, 198–208.

Kiel, J. et al. 2016. A decision support system for the resilience of critical transport infrastructure to extreme weather events. *Transportation Research Procedia* **14**, 68-77

Nemrym, F., Demirel, H. 2012. *Transport and climate change: a focus on road and rail transport infrastructures*. JRC72217.

Pitilakis, K. et al. (eds). 2014. *SYNER-G: typology definition and fragility functions for physical elements at seismic risk*. Springer.

Stefanidou, S.P., Kappos, A.J. 2017. Methodology for the development of bridge- specific fragility curves. *Earthq. Eng. Struct. Dyn.* **46**(1), 73-93.