Restoration models for quantifying flood resilience of bridges

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Abstract

Bridges are the most vulnerable assets of our transport networks. They are disproportionately exposed to and hit by multiple natural hazards, with flooding being the leading cause of bridge failures in the world. Their performance is constantly challenged by the combined effects of natural hazard stressors, e.g. flash floods, exacerbated by climate change, ageing, increasing traffic volumes and loads. Bridges are vulnerable to scour and other flood-related impacts, such as hydraulic forces and debris accumulation. In order to assess and quantify the resilience of flood-critical bridges and subsequently deploy bridge resilience models aiming at building resilience into transport networks, it is essential to use reliable fragility, capacity restoration and traffic reinstatement metrics and models. It is surprising that, despite the importance of bridges and their high vulnerability to hydraulic actions, there is no available recovery models. The latter can help quantify the pace of post-flood capacity and functionality gain for facilitating well-informed decision making for reliable prioritisation and efficient allocation of resources in transport networks. The main barrier is the nature and complexity of recovery actions, which encompass engineering, operational, owner resources and organisational challenges, among others. This paper, for the first time in the international literature, aims at filling this gap by generating a set of reliable recovery models that include both bridge reinstatement (traffic capacity) and restoration (structural capacity) models based on a detailed questionnaire that elicits knowledge from experts. Recovery models are then presented and validated for spread and deep foundations for a typical reinforced concrete bridge, including restoration task prioritisation and scheduling, inter-task dependencies, idle times, durations and cost ratios for different damage levels, as well as the evolution of traffic capacity after floods.

keywords: *bridge; transport; infrastructure; damage levels; restoration; reinstatement; resilience; flood; scour; survey; cost ratio; idle time; functionality loss*

1 Introduction

Bridges are particularly vulnerable assets of our transport networks nevertheless they are important components (Guikema and Gardoni 2009). Flooding is the greatest risk to infrastructure assets and bridges all over the world. The largest percent of recorded bridge failures is hydraulic induced (Kirby et al. 2015), and in particular scour (S) that is triggered by floods, debris accumulation (D) and hydraulic forces (F), which may be exacerbated due to climate change (e.g. Stern et al. 2013, Dikanski et al. 2016). In the USA, hydraulic actions (SDF), have been recognized as the most disastrous causes of bridge failures, representing more than 50% of the cases (Wardhana and Hadipriono 2003, Cook et al. 2015;), with an average annual restoration cost of about $50m (Lagasse et al. 1995). Based on a record of scour-induced failures in the UK over a period of more than 173 years, it is estimated that the annual probability of bridge failure is 27%, i.e. one out of three river bridges might be damaged due to flood (Van Leeuwen and Lamb, 2014). As an example, during the 2009 floods in Cumbria, UK, at least 20 bridges were damaged, resulting in £34m of repair 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 cost of damage to the road network after a series of extreme weather events between 2011 and 2012 in Queensland, Australia, has been estimated to more than $7bn, with 5% of the cost was for bridges (Pritchard, 2013). During the 2014 floods in Serbia, 307 bridges were affected, the total losses for transport infrastructure were estimated to €166.5m, with a reconstruction cost of €128m (World Bank Group 2014).

As the climate is changing, heavy precipitation is intensifying on global average (Donat et al. 2020). Local extremes have increased in frequency, ferocity and duration posing a significant threat to all classes of transport infrastructure (Pregnolato et al. 2020). Bridges are arguably one of the worst affected assets with future projections anticipating that in critical regions such as New Mexico or West Texas bridge vulnerability to scour may escalate to 90% by the second half of the 21st century (Neumann et al. 2015). Through a comprehensive analysis of river discharge records from 3,738 gauging stations in Europe for the period 1960-2010, Blöschl et al. (2019) result in projections for the end of the twenty-first century that suggest upward trends in flooding in north-western Europe due to increasing precipitation. In agreement with a number of similar recently published research studies (e.g. Do et al. 2019, Bertola et al. 2020), such results support the growing awareness that flood risk analysis and management can no longer ignore the challenge of climate change, especially when focused on transport infrastructure, which is long-lived in nature. The climate change effect is further discussed in section 3.6.

There has been extensive research on SDF actions to bridges, including numerical simulations (Ju, 2013, Prendergast et al. 2013, Klinga and Alipour 2015, Kim et al. 2017, Tubaldi et al. 2018, Scozzese et al. 2019), analytical solutions for scour depth prediction (Hosseini and Amini, 2015), physical model testing (Roca and Whitehouse 2012, Tubaldi et al. 2019), expert elicitations (Lamb et al. 2017) and monitoring studies (Prendersgat and Gavin 2014, Maroni et al. 2019, Maroni et al. 2020, Boujia et al. 2019). Furthermore, there are available guidelines for the design and assessment of bridges exposed to SDF actions (FHWA 2012, Kirby et al. 2015). In this respect, it is widely recognised that Quantitative Risk Analysis (QRA) is important, especially for the resilience and adaptability of critical assets (COE 2011, FHWA 2013), and more recently, quantitative resilience assessment frameworks (Deco et al. 2013, Dong and Frangopol 2015, 2016) have been proposed for bridges and infrastructure exposed to multiple hazards and extreme events (Alipour 2017, Ganin et al. 2017, Argyroudis et al. 2020a, Smith et al. 2021). The majority of these frameworks consider the four 'R' principles of resilience as per Bruneau et al. (2003), i.e. the Robustness, which describes the inherent strength or resistance in a system to withstand external demands, e.g. hydraulic (SDF) actions, without degradation or loss of functionality, the Redundancy, reflecting system properties that allow for alternate options, choices, and substitutions under stress, the Resourcefulness, expressing the capacity to mobilise needed resources and services in emergencies, and the Rapidity, which defines the speed with which disruption can be overcome. Resilience-based design and assessment are the new concepts that are being introduced in practical applications of critical infrastructure and are expected to be included in the next generation of provisions and guidelines, e.g. see REDi system by Almufti and Willford (2013).

Robustness is commonly quantified through fragility functions, which give the probability of the bridge exceeding defined limit states, e.g. serviceability and ultimate, for a given hazard intensity, e.g. water discharge or scour depth. Fragility functions can be derived from empirical, analytical, expert elicitation and hybrid approaches (Argyroudis et al. 2019). Fragility functions have been proposed for a combination of scour and other accidental actions, such as seismic loads (Banerjee and Prasad, 2013, Wang et al. 2014, Guo et al. 2016, Yilmaz et al. 2016, Torres et al. 2017, Yuan et al. 2019) or vehicular loads and barge collisions on piers (Kameshwar and Padgett 2018a,b). However, very little research is available on fragility assessment of bridges focusing on SDF actions (Argyroudis and Mitoulis 2021, Kim et al. 2017, Hung and Yau 2017, Tanasić and Hajdin 2018), while existing frameworks also neglect the critical role of structural ageing and deterioration due to preceding events (Zanini et al. 2017). The latter has been recently addressed in studies dealing with earthquake response in the context of probabilistic life-cycle analysis (Frangopol et al. 2017). Yet, the scarcity of available restoration functions, i.e. functionality *vs.* recovery time relationships, which are essential for the prediction of recovery paths and ultimately for the quantification of Rapidity, are currently restricted to dealing with the seismic hazard (Gidaris et al. 2017).

Restoration functions are typically based on expert judgment, following a linear, e.g. Bocchini et al. (2012), stepwise, e.g. Padgett and DesRoches (2007), or lognormal, e.g. HAZUS-MH (2011) formulation and they may consider complete and partial closure of bridges (Kameshwar et al. 2020). Development of reliable models is a challenge because recovery time depends on a multitude of parameters that are difficult to generalise. Such are the availability of resources, national/local policies, practices of the owner, the specific type and extent of damage, among others. What is more, in the case of bridges functionality encompasses the recovery response of sub-components (Mackie and Stojadinovic 2006, Ghosh and Padgett, 2011), e.g. bearings, piers, deck, abutments, foundation, which involves a variety of restoration practices and uncertainties. Restoration times for the different tasks and components can vary considerably, while a range of values or a mean value and a standard deviation can describe the expected recovery time to account for uncertainties in the recovery process (Bradley et al. 2010, Karamlou and Bocchini, 2017a). Some quantifications of damage given in this paper, e.g. crack width, settlements and pier tilting is based on the characterisation of damage after earthquakes and expert judgment. In general, the available restoration models are mainly for earthquake hazard, while little information for other hazards is provided, e.g. by HAZUS-MH (2011) for tsunami and Koliou and van de Lindt (2020) for tornadoes. The available restoration functions of scoured bridges are very limited (Misra et al. 2020; Aydin et al. 2018) and thus we are unable to estimate losses and model the recovery process at bridge and/or network level after floods. Therefore, it is not possible to accurately evaluate the resilience of bridges and their impact on the operation of the networks.

Therefore, this is a capability gap that needs filling with new and reliable restoration functions which can reflect realistically, the rapidity of the recovery and the reinstatement actions required throughout the post-flood management actions. It is clarified here that restoration tasks are assumed to include, to some extent, structural interventions, e.g. strengthening of a scoured foundation, whereas reinstatement tasks refer to non-structural interventions, e.g.

removal of debris from the bridge deck. On the basis of this established knowledge gap, this paper presents a comprehensive survey, which elicits knowledge from experts in an effort to develop restoration and reinstatement models for scour critical bridges. This first effort of data collection aims to produce reliable resilience models for representative bridges. Due to the acknowledged absence of restoration models of flood-induced damage on bridges, a comprehensive questionnaire was prepared, and an ongoing survey is being conducted as a means to develop restoration functions for bridges. Thus, this paper provides for the first time well-informed restoration and reinstatement functions for scoured bridges, while standardises both damage and functionality levels for defining the damage and restoration functions. The paper also introduces multiple and mutually dependent tasks, allowing for scheduling of restoration, after quantifying idle times and restoration costs per predefined damage states as part of the survey questionnaire. In what it follows, a brief description of the survey questionnaire is given and results in terms of restoration functions are provided and validated. The findings are expected to inform county councils, owners and stakeholders, and provide valuable information for managing efficiently their assets prior and after catastrophic events.

2 Restoration strategy for scoured bridges based on elicitation

This restoration strategy for scour-critical bridges refers to reinforced concrete bridges with either surface or deep foundations with piles. The strategy is being encapsulated by the questionnaire, which aims at identifying the restoration tasks, the dependencies and duration of these tasks per damage level, as per section 2.2 below. The first part of the survey contains a number of questions, including a self-assessment of the expert's knowledge and professional experience on flood-induced bridge damage and restoration after floods, reflecting a measure of experts' confidence. More detail about the questionnaire is given in section 2.3, including input for the idle and restoration time in days, to quantify the pace of recovery on the basis of the (partial/percentage) reinstatement of traffic capacity after the damage, as well as the sequence of the restoration tasks and an estimate of the cost. The questionnaire and th answers by the experts are available in the accompanying data in brief publication (Mitoulis and Argyroudis, 2021). The questionnaire will be extended to include masonry, stone, timber and composite bridges, by adjusting the description of damage levels to the typology of these structures.

2.1 Benchmark bridge, damage and functionality loss due to floods

The expert is expected to assess and provide feedback with regard to the recovery of the damaged bridge per damage level for a given typical 3-span bridge, which was the **benchmark bridge** of this study. The deck of the bridge is considered to be either continuous, in which case a rigid connection to the piers and/or abutments was considered, or simply supported through bearings, where the deck has a continuity slab and comprises of precast I-beams. The above two alternatives cover a wide range of modern bridge construction methods. The number of spans and the geometry of each structural component were not considered in this questionnaire due to their variability. Instead, a typical 3-span bridge was assumed. The reference bridge of this questionnaire has a total length of 101.5 m and three spans of equal length of 33.5 m. The deck has a total width of 13.5 m, the height of the abutments is 8.0 m, the footing has a thickness of 1.0 m and is 5.5 m long. The piers have a height of 10.0 m. The shallow foundation footing has a thickness of 1.5 m and is 3.5 m long (Figure 1). It is assumed that the bridge is of average importance, meaning that the bridge restoration is not drastically affected by matters in respect to, e.g. detour time and length, redundancy of the network, vehicle traffic flow and consequent unacceptable community severance, such as inaccessible islands or hospitals (Bocchini and Frangopol 2012, BD97/12, 2012).

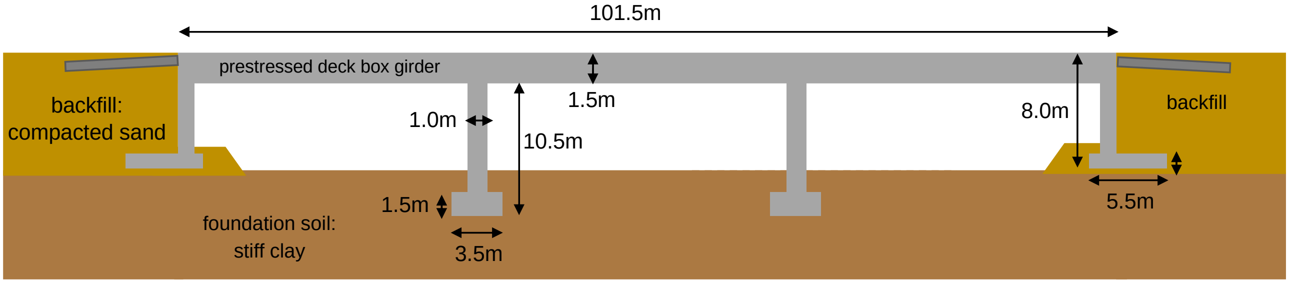


Figure 1. The 3-span prestressed concrete reference bridge with spread foundation

A qualitative description of failure mechanisms due to hydraulic actions has been previously provided by JBA Trust (2014) and Lebbe et al. (2014, 2018). Also, in the bridge inspector's reference manual, chapter 12 (Ryan et al. 2012) a detailed qualitative record of potential damage on scoured bridges is provided for bridge substructures. Nevertheless, the latter does not include thresholds for quantification of damage on the basis of crack density and width, settlements, rotation, displacements and deflections, thus, no damage levels can be identified. In addition, this reference does not provide information about factors leading to functionality (traffic) loss, e.g. due to debris and water accumulation on the deck. Therefore, it is partially useful for the generation of fragility and functionality loss curves, which are related to the capacity and operability of the bridge (Argyroudis et al. 2019). Likewise, the identification of the damage levels for the restoration and reinstatement of the bridge is also required for building resilience models, for which no adequate information is currently available (Kammouh et al. 2018). This is the knowledge gap that this questionnaire fills, which provides well-informed damage criteria and thresholds for each bridge component, considering structural and/or geotechnical damage modes.

In particular, the experts are requested to provide their estimates for different **damage levels (DL)**, i.e. minor, moderate, extensive and severe, for the different bridge components, i.e. foundations, piers, abutments and wingwalls, bearings, deck, backfill and approach slab. The DL are guided by sketches (qualitative) and quantitative descriptions of the damage for each bridge component as illustrated in Table 1, below for spread and deep foundations. The DL were identified based on analyses on PLAXIS modelling where the failure of bridges due to scour were vetted (Argyroudis et al. 2019, Yuan et al. 2019). The DL for other bridge components are given in Annex A. For identifying the damage, relevant criteria and thresholds were defined. These enabled the damage characterisation and they are based on the literature and expert judgement, as described in the introduction of this paper and the previous paragraph. The various damage modes and levels, as a result of damage of a particular structural component, may not occur simultaneously. In this case, it is considered that the worst-case scenario prevails, i.e. the worst damage mode of any component, and this defines the corresponding DL. In addition, hydraulic-induced disruptions to bridge deck due to non-structural effects are defined (Table 2) and **functionality loss levels** are described based on the accumulation of water and debris due to overtopping or flooding, the deterioration of the pavement and/or failure of markings and signage. Both the DL and the functionality loss influence the reinstatement of the bridge traffic as discussed in sections 3.2 and 3.3.

Table 1. Hydraulic induced damage to bridge spread and deep foundations

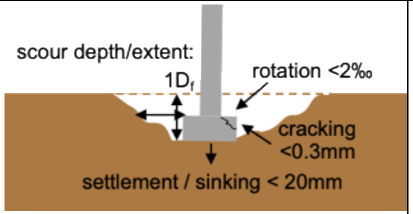
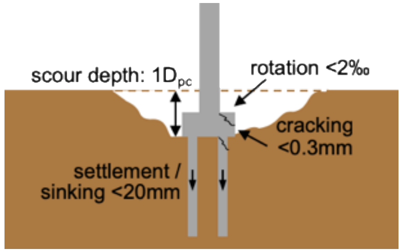
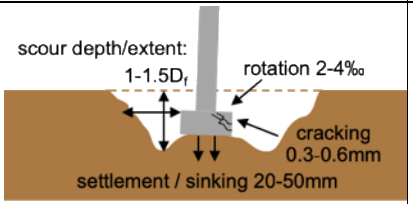
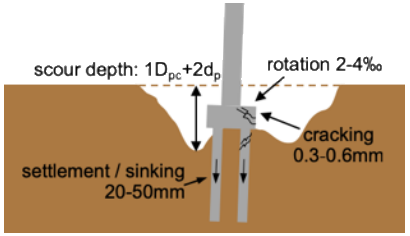
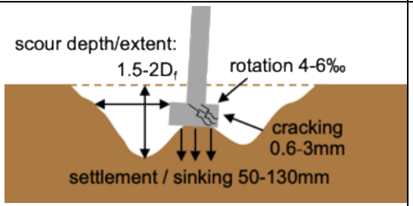
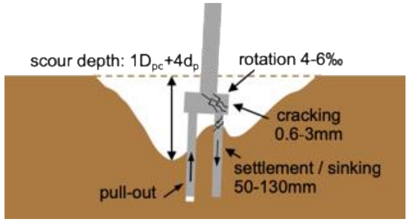
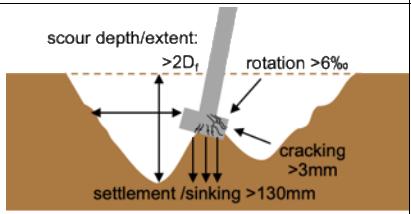
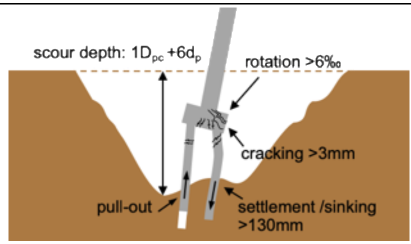
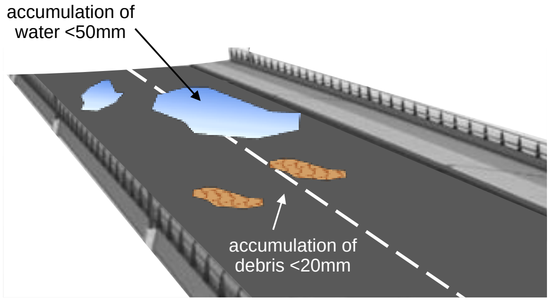
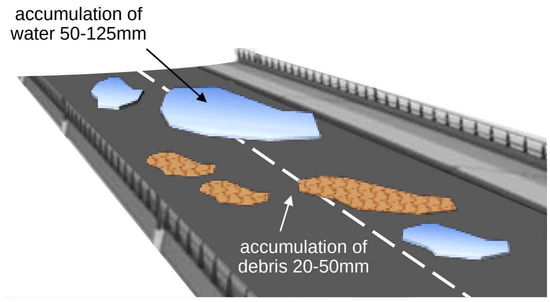
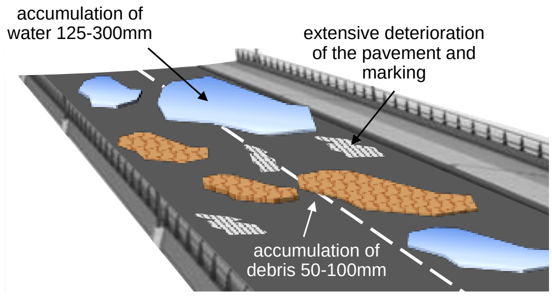
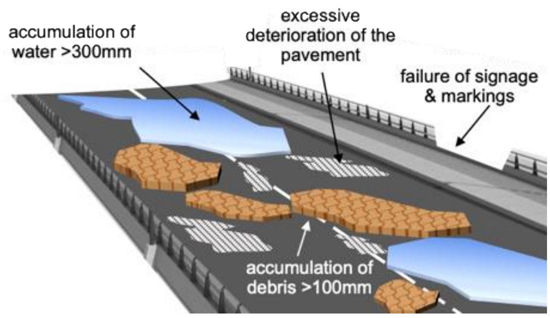
damage level (DL)	spread foundation		deep foundation	
minor	- Foundation settlement/sinking: < 20 mm - Foundation rotation/differential settlement: < 2‰ - Minor spalling (damage requires no more than cosmetic repair): crack width < 0.3mm - Scour hole depth and extent: $1.0D_f$ (where D_f is the foundation depth) - Safety Factor: > 3		- Buckling causing minor spalling and cracking: crack width < 0.3mm - Scour hole depth: $1.0D_{pc}$ (where D_{pc} is the foundation depth at the pile cap level) - Deep foundation settlement/sinking or pull-out: <20 mm - Deep foundation/pile cap rotation: <2‰	
moderate	- Foundation settlement/sinking: 20-50 mm - Foundation rotation/differential settlement: 2-4‰ - Moderate cracking and spalling (foundation structurally still sound): crack width 0.3-0.6mm - Scour hole depth and extent: $1.0\text{-}1.5D_f$ - Safety Factor: 2-3		- Buckling causing moderate spalling and cracking: crack width 0.3-0.6mm - Soil is washed out, piles are revealed, scour hole depth: $1.0D_{pc}$ + $2d_p$ (where d_p is the pile diameter) - Deep foundation settlement/sinking or pull-out: 20-50mm - Deep foundation/pile cap rotation: 2-4‰	
extensive	- Foundation settlement/sinking: 50-130 mm - Foundation rotation/differential settlement: 4-6‰ - Foundation degrading without collapse – shear failure (foundation structurally unsafe): crack width 0.6-3mm - Reinforcement yielding - Scour hole depth and extent: $1.5\text{-}2.0D_f$ - Safety Factor: 1-2		- Buckling causing extensive spalling and cracking: crack width 0.6-3mm - Soil is washed out, piles are revealed, scour hole depth: $1.0D_{pc}$ + $4d_p$ - Deep foundation settlement/sinking or pull-out: 50-130mm - Deep foundation/pile cap rotation: 4-6‰ - Reinforcement yielding	
severe	- Foundation settlement/sinking: >130 mm - Foundation rotation/differential settlement: >6‰ - Overturning of the foundation: crack width >3mm - Reinforcement failure - Scour hole depth and extent: $>2.0D_f$ - Safety Factor: <1		- Buckling causing excessive cracking: crack width >3mm - Soil is washed out, piles are revealed, scour hole depth: $1.0D_{pc}$+ $6d_p$ - Deep foundation settlement/sinking or pull-out: >130mm - Deep foundation/pile cap rotation: >6‰ - Reinforcement failure	

Table 2. Hydraulic induced disruptions to bridge deck

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

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

2.2 Restoration tasks and mutual dependencies

The questionnaire includes a breakdown of the restoration process in 23 tasks (Ri) for the bridge foundations, piers, abutments and wingwalls, bearings, deck, and the backfill with the approach slab, as well as some generic ones referring to ground improvement and river flow alterations/cofferdam (Table 3). The numbering of the Ri tasks is not related to the sequence and order of the restoration tasks. The order is provided by the expert answers and informed by engineering judgement, see Table 4a and 4b. The questionnaire also offers the opportunity to the experts to add tasks in case they believe are relevant. For example, additional and complementary tasks can be harvested by available online datasets (Misra et al. 2019). Such tasks can include rebuilding the approach slab, use of cement stabilised sand, use of geotextiles and/or micropiles. Additional upstream measures may also be considered, e.g. building of weirs and installation of scour counter measure devices, such as A-jacks. The experts were requested to provide, to the best of their knowledge, the maximum and minimum duration required for each one of the restoration tasks. Table 3 shows in columns (3) and (4) the average of the values provided for the minimum and maximum durations for each restoration task based on the values provided by the experts-no weighting was applied. Columns (5) gives the mean value of columns (3) and (4), while column (6) shows the average standard deviation of minimum and maximum values. It seems that, based on Table 3, the most time-consuming and tedious tasks are the ones involving the replacement of critical structural components (e.g. R17, R18, R23) and the installation of new deep foundation (R15). Likewise, the standard deviation (std dev) is greater for restoration tasks which are lengthy.

It is understood that the same task might differ in terms of duration across different damage levels (DL). For instance, R5 that refers to the repair of cracks and spalling with epoxy and/or concrete might require half of the mean time in case slight damage occurs in the bridge, in comparison to the case where severe damage is encountered. This dependence of the restoration task duration on the DL is reflected by the weighting factors given in columns (7), (8), (9) and (10) of Table 3, corresponding to minor, moderate, extensive and severe damage. To account for the dependency of the duration of Ri on the DL, an adjustment of the duration of the tasks was performed based on expert judgment through four different sets of weighting factors. In particular, (i) a weighting factor equal to 1.0 for all DL was considered to be appropriate for restoration tasks R7, R15 to R20, R22 and R23, meaning that the restoration time is independent from the DL; (ii) a second set of weighting factors of 0.7, 0.8, 0.9 and 1.0 for the minor, moderate, extensive and severe DL, correspondingly, and this applies to restoration tasks R1 to R4 and R11 to R14; (iii) weighting factors equal to 0.5, 0.7, 0.85 and 1.0 for the DL correspondingly, and this applies to R5, R6, R10 and R21; (iv) weighting factors equal to 0.0, 0.4, 0.7 and 1.0 for R8 and R9. The zero value in the last set of weighting factors means that minor damage would not require this restoration task, whereas the same task is required for moderate to severe damage with values of weighting factors ranging from 0.4 to 1.0, e.g. jacketing for piers would not be required for minor damage.

Table 4 shows the restoration tasks (Ri), which are expected to be implemented on a bridge that is damaged due to scour and other hydraulic-related damage, e.g. debris accumulation. These tasks are differentiated upon the type of the bridge structural and geotechnical components, e.g. the foundations, the piers, the abutments, as shown in the first column of the table, whereas the first line of the same table shows the nature of the expected intervention, i.e. whether the tasks is of structural (STR), geotechnical (GEO) nature or other (OTH). For example, R5 and R8 tasks are repairs related to crack filling with epoxy and jacketing, which are largely interventions of structural nature, whereas R14 is ground improvement, i.e. geotechnical task. The bridge restoration process is also expected to include a number of tasks which are common, across different bridge components and damage levels. For instance, engineering tasks (ENG) such as emergency inspection, site investigation and assessment, preliminary design, detailed design or advisory services during construction, administrative tasks (ADM), e.g. contract administration, and structural health monitoring tasks (SHM), i.e. monitoring and inspection during construction and monitoring after the completion of repairs. It is also highlighted that the tasks shown in Table 4 are typical tasks and do not include specialised tasks such as for example the use of cranes for accessing the bridge. Also, it aims at covering typical bridges, but it does not cover special structures, such as cable-stayed or suspension bridges. Also, the methods for strengthening here do not include the use of additional structural components, e.g. the use of fibre-reinforced polymers (FRP) and/or the use of external prestressing, as these were considered to be beyond the scope of this research. Yet, it is likely that the decision to invest in restoring a bridge that suffered scour-induced damage might lead to additional interventions, not necessarily related to the damage due to floodings, such as jacketing and use of resin crack fillers, as provided in R5 and R8. For example, whilst the bridge is restored after a flood, it may also be upgraded to be able to receive greater traffic loads and/or strengthened and/or partially replaced if critical structural components are deteriorated due to e.g. corrosion.

Table 3. Duration of restoration tasks and weighting factors per damage level

code	restoration task	duration (days)				weighting factors			
		minimum	maximum	mean	std dev	minor	moderate	extensive	severe
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
R0	no action is required	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*
R1	armouring countermeasures and flow-altering/cofferdam	5.6	24.8	15.2	13.4	0.7	0.8	0.9	1.0
R2	temporary support per pier	3.2	9.2	6.2	4.2	0.7	0.8	0.9	1.0
R3	temporary support of one abutment	3.0	10.0	6.5	4.6	0.7	0.8	0.9	1.0
R4	temporary support of one deck span /segment (midspan or support)	3.6	10.8	7.2	3.9	0.7	0.8	0.9	1.0
R5	repair cracks and spalling with epoxy and/or concrete	3.4	19.0	11.2	13.0	0.5	0.7	0.85	1.0
R6	re-alignment and/or leveling of pier	12.0	29.8	20.9	23.6	0.5	0.7	0.85	1.0
R7	re-alignment of bearings	2.8	10.0	6.4	6.8	1.0	1.0	1.0	1.0
R8	jacketing or local strengthening (pier or abutment or foundation)	11.4	35.0	23.2	30.0	0.0	0.4	0.7	1.0
R9	jacketing or local strengthening (deck)	13.8	32.8	23.3	23.3	0.0	0.4	0.7	1.0
R10	re-alignment of deck segment	8.2	18.2	13.2	17.9	0.5	0.7	0.85	1.0
R11	erosion protection measures	6.8	16.3	11.5	6.4	0.7	0.8	0.9	1.0
R12	rip-rap and/or gabions for filling of scour hole and scour protection	6.0	23.4	14.7	13.5	0.7	0.8	0.9	1.0
R13	removal of debris	2.9	7.4	5.2	4.7	0.7	0.8	0.9	1.0
R14	ground improvement per foundation	11.2	32.0	21.6	21.8	0.7	0.8	0.9	1.0
R15	installation or retrofitting of deep foundation system	33.8	66.0	49.9	49.3	1.0	1.0	1.0	1.0
R16	extension of foundation footing	20.8	46.0	33.4	32.1	1.0	1.0	1.0	1.0
R17	reconstruction/replacement of the abutment and wingwalls	31.0	72.0	51.5	41.1	1.0	1.0	1.0	1.0
R18	reconstruction/replacement of the pier	42.0	78.0	60.0	44.3	1.0	1.0	1.0	1.0
R19	temporary support and replacement of the bearings	3.8	9.4	6.6	3.8	1.0	1.0	1.0	1.0
R20	replacement of the backfill and approach slab and mudjacking	12.0	32.0	22.0	11.5	1.0	1.0	1.0	1.0
R21	replacement of expansion joint	2.0	7.2	4.6	3.1	0.5	0.7	0.85	1.0
R22	demolish/replacement of a deck span/segment	22.2	51.0	36.6	23.2	1.0	1.0	1.0	1.0

R23	demolish/replacement (part) of the bridge	88.8	334.0	211.4	133.8	1.0	1.0	1.0	1.0
R24	*please add customised task*	-	-	-	-	-	-	-	-

Table 4. Types of diverse restoration tasks (Ri) for different bridge components

bridge component \ type	**STR**: structural	**GEO**: geotechnical	**OTH**: other
foundations	R5, R8	R11, R14, R15, R16	R1
piers	R2, R5, R6, R8, R18	R12	R1, R13
abutments & wingwalls	R3, R4, R5, R8, R17	R12, R14, R15, R16	R1
bearings	R7, R19		R1
deck	R5, R9, R10, R22		R1, R13, R21
backfill & approach slab		R11, R12, R14, R20	

- **STR**: structural; **GEO**: geotechnical; **OTH**: other common tasks, including: engineering-ENG; administrative-ADM; structural health monitoring-SHM
- if R23 is chosen then this refers to all types and structural components

Table 5. Restoration tasks (Ri) execution dependencies with tasks (Rj) and temporal overlap.

Rj \ Ri	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23
R1		1	1	1	0.5	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0.5	0.5	1	1
R2	0		0	0.5	0.5	1	0.5	1	1	0.5	0	0	0	0	0	0.5	0.5	1	1	0	0	1	0
R3	0	0		0.5	0.5	0	0.5	1	1	0.5	0	0	0	0	0	0	1	0.5	0.5	0	0	1	0
R4	0	0.5	0.5		0.5	0	1	0.5	1	1	0	0	0	0	0	0	1	1	1	0	0	1	0
R5	0	0	0	0		0	0	0.5	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0.5	0
R6	0	0	0	0.5	0.5		0.5	0.5	1	0.5	0	0	0	0	0	0.5	0	0	0.5	0	0.5	1	0
R7	0	0	0	0.5	0	0.5		0.5	1	0.5	0	0	0	0	0	0	0	0	0.5	0	0.5	1	0
R8	0	0	0	0.5	0.5	0	0.5		0.5	0	0	0	0	0	0	0.5	0	0	0	0	0	0.5	0
R9	0	0	0	0.5	0.5	0	0	0		0.5	0	0	0	0	0	0	0	0	0	0	0	0.5	0
R10	0	0	0	0.5	0.5	0	0.5	0	0.5		0	0	0	0	0	0	0	0	0.5	0	1	1	0
R11	0	0.5	0.5	0	0.5	0.5	0	0.5	0	0		0.5	0	1	1	1	0.5	0.5	0.5	0.5	0	1	1
R12	0	0.5	0.5	0	0.5	0	0	0.5	0	0	**0.5**		0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	1	1
R13	0	1	1	1	1	1	0	1	1	1	1	1		1	1	1	1	1	1	0.5	1	1	1
R14	0	0.5	0.5	0.5	0.5	0	0	0.5	0	0	0	0	0		0.5	0.5	0.5	0.5	0.5	0	0	0.5	1
R15	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0		0	0.5	0.5	0.5	0	0	0.5	1
R16	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0.5		0	1	1	0	0	0.5	1
R17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.5	0.5	0.5	1	1	0.5
R18	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0		1	0	1	1	0.5
R19	0	0	0	0.5	0	0	1	0	1	1	0	0	0	0	0	0	0.5	0		0	0.5	1	0
R20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0		1	0	0.5
R21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
R22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		1
R23	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	1	1	

Table 5 shows the interdependencies of the typical restoration tasks (Ri) for bridges that are damaged after flood events. These dependencies are aiming at reflecting both the succession, i.e. the sequence of tasks as a matter of task prioritisation in execution, and the potential temporal overlap, i.e. quantification of the potential overlap of the task execution during the restoration process (Karamlou and Bocchini, 2017b). Table 5 has 23 columns and an equal number of rows and each cell corresponds to the dependencies between all tasks, i.e. R1 to R23. The diagonal of the table does not have values as it shows the dependency of a task Ri from itself, thus does not have a logic meaning. The values of each cell show the level of both **execution** and **temporal** dependency. The values are expected to be extracted from the table by reading task Ri from row 1 and link this to task Rj from column 1. For example, the dependency of task Ri, where i=11 from task Rj, j=12, is 0.5, meaning that the completion of erosion protection measures would depend to some extent - 50% in this case - from the installation of rip-rap and/or gabions for filling the scour hole. The quantification of this dependency is based on expert judgement. The same value, i.e. 0.5, also means that a temporal overlap of 50% exists for the two tasks, e.g. if Ri requires 10 days to complete and task Rj requires 14 days to complete, the completion of both tasks would require 7 days (50% of the Rj 14-day long task), plus an additional 3 days for the completion of the 10-day long duration of Ri, see also Figure 4. The table contains a three-level dependency rule for these tasks, i.e. only three values were considered that are 0, 0.5 and 1, in the absence of more accurate evidence. The value 0 means that there is no direct dependency between the tasks, the 0.5 is the dependency that was described before, i.e. 50% execution and temporal dependency, whilst a dependency with a value equal to 1 is the case where the execution of task Ri (of row 1) requires for tasks Rj (of the first column) to be 100% completed. An example of this dependency is the case of R2-R1, i.e. the temporary support of a pier (R2) would require the completion of armouring countermeasures and flow-altering/cofferdam (R1). Thus, if the duration of tasks for Ri is 10 days and the duration of Rj is 20 days, it means that Rj should be completed before Ri takes place, leading to a total duration for the completion of both tasks of 30 days in total for this example. These dependency values were based on engineering judgment and were not part of the questionnaire. A greater granularity can be achieved if real data becomes available and use e.g. a completion step of 0.1, i.e. 10%.

2.3 Restoration process based on the questionnaire

Based on Table 6, the experts are requested to provide, for each damage level and for each bridge component, the following estimates:

(i) **idle time** (column 2, 3), i.e. an estimate of the minimum and the maximum time before the initiation of any restoration work. This time might include but is not limited to emergency response, removal of standing water, inspection and condition assessment, site investigation, structural and foundation evaluation, check of pile stability with new unsupported lengths, design of measures, as well as organisational barriers. This time does not include any work or construction on the bridge, or delays due to other hazard events, e.g. intermediate floods. The idle time estimation is separated from the restoration scheduling model, as this should not influence the formulation of the resilience model due to its great fluctuation. This is in line with other publications (Bocchini and Frangopol, 2012, Bocchini et al. 2012, Argyroudis et al. 2020b).

(ii) **traffic capacity of the bridge after damage** (% of the normal bridge capacity) (column 4), is the metric of "traffic restriction" for the bridge for each DL and for each point in time after the commencement of the restoration works. The experts were asked to provide the expected traffic carrying capacity (0, 50 or 100%) at time 0, 3, 15, 30, and 60 days following the initiation of restoration works. The selected % traffic capacity accounts only for the effect of damage of that specific component to the functionality of the bridge, e.g. when considering bearings, it is assumed that columns, footings, and abutments are intact. On day 0, the traffic capacity is linked solely on the structural capacity of the bridge structural components, except the case of the deck, which might include non-structural obstructions, e.g. accumulation of water or debris that obstruct the traffic. Thus, the traffic capacity on day 0 is the remaining capacity of the bridge before any restoration task commences.

(iii) **prioritisation of restoration tasks** (column 5), i.e. the repair tasks that may be applied in order to restore the bridge component to its normal operation based on the list of tasks Ri given in Table 3, considering the reasonable order of the tasks, e.g. “R6, R5”, means that re-alignment of the pier (R6), is preceding the repair of cracks with epoxy (R5). It is noted that the typical post-disaster level of resources is available for repair, while the current best practices for repair procedures are considered.

(iv) **cost ratio** (column 6), is an estimation for the cost of the repair tasks defined in column 5, as a ratio of the construction cost of the entire bridge. For example, repair cost ratio equal to 0.15 means that the cost of the restoration tasks is equal to 15% of the re-construction cost, or in other words, if the bridge cost is 3.0 million, its restoration is 3 x 0.15= 0.45 million.

(v) Finally, the experts can provide **comments**, e.g. to specify if their estimations were based on a specific case-event, and any additional comments they may have throughout the process of completing the survey regarding the format, damage levels, bridge functionality, repair procedures, or other.

Table 6. Questionnaire with indicative responses for spread foundation, eliciting idle time (col 2, 3), level of traffic capacity (%) (col 4) for different damage levels and times (0, 3, 15, 30, 60 days) from the initiation of restoration, including corresponding restoration tasks (col 5) and cost ratios (col 6).

damage level (DL) *(see Table 1 for description)*	**idle time in days** (before any restoration works)		**reinstatement time in days (after the initiation of the restoration works)**															**restoration tasks & prioritisation** *(see Table 3)*	**cost ratio** *(% of replacement cost of the bridge)*
			0			**3**			**15**			**30**			**60**				
	min	**max**	**% traffic capacity of the bridge after damage**																
(1)	(2)	(3)	(4) *(check mark "X")*															(5)	(6)
			0	50	100	0	50	100	0	50	100	0	50	100	0	50	100		
minor	4	14		X				X			X			X			X	R12, R5	5
moderate	10	30	X			X				X				X			X	R1, R12, R5	8
extensive	25	45	X			X			X					X			X	R1, R6, R12, R14, R2, R16, R5	15
severe	30	70	X			X			X			X					X	R1, R6, R12, R14, R2, R16, R15, R5	30
comments:																			

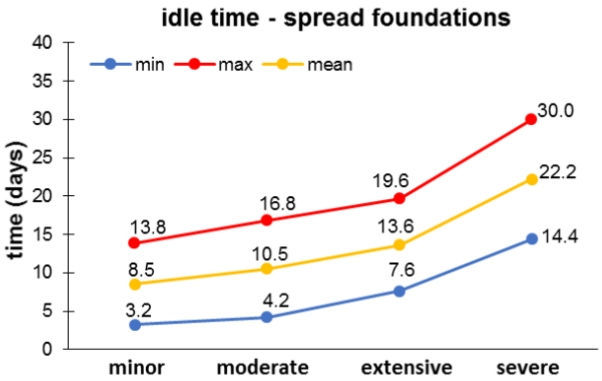
3 Results and discussion for scour-critical bridge foundations

3.1 General remarks

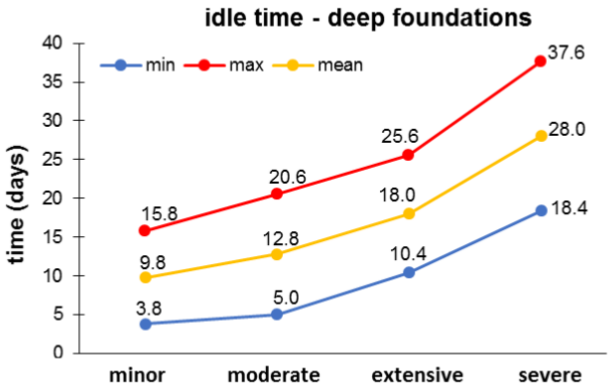
The soil, the water, the bridge and the backfills comprise an interacting system, which cannot be assessed separately. This means that any failure of the soil is expected to potentially lead to damage in the foundations, the piers, the bearings, the deck, the abutments and the backfills. This section provides results for the foundations, which are the structural components affected most after floods (Tanasić and Hajdin 2018). The rest of the bridge components are also included in the questionnaire, but not examined in this paper. In what follows, is the restoration and reinstatement models for bridges having surface and deep foundations based on several interviews and, additionally, expert responses from six completed questionnaires by experts coming from academia, consultants and scientists from research institutions, all declared having similar confidence and level of expertise. It is underlined that the results based on column (4) of the questionnaire do not match with the total time of the restoration tasks provided in column (5) of the same table. It is reminded that column (4) refers to the reinstatement of the traffic of the bridge, whilst column (5) reflects the prioritisation of tasks for structural rehabilitation. As a result, the total times of column (4) per damage level are different from the cumulative duration of the restoration tasks, which is considered to be reasonable because structural restoration does not necessarily lead to traffic disruptions (Monnier et al. 2015). Thus, the times of column (4) are smaller than the cumulative times of column (5). The latter publication also provided evidence and essential validation for the proposed models (see section 3.4).

3.2 Idle time and cost

Figure 2 shows the variability in the **idle (lag) time** after the damage occurrence based on experts' estimation. For the estimation of the illustrated minimum, mean and maximum value per damage level, the average values were calculated. The mean value is the average of the minimum and maximum value shown on the figure. What is observed that the average idle time for minor, moderate, extensive and severe damage is increased from 8.5 to 10.5, 13.6 and 22.2 days correspondingly for the spread foundations. It is also apparent based on the experts' opinions that the uncertainty in the idle time increases from minor to severe damage, as for example for the minor damage the mean value may fluctuate 5 days (8.5 ± 5 days), whereas the idle time is 22.2 ± 7.8 days for the severe damage. The post-flood idle time is greater in deep foundations (see Figure 2b) ranging from 9.8 to 28 days. Likewise, the experts also reflected a higher uncertainty in the lag time with fluctuations of e.g. 6 days (9.8 ± 6 days) for the minor and 9.6 days (28 ± 9.6 days) for the severe damage. It is realised that the restoration of bridges with deep foundations requires more pre-restoration work in terms of inspection of the buried and additional structural components and design and strengthening of piles. Also, two of the experts assumed that the idle time after minor damage is greater than the lag time after moderate and extensive damage, as an indication that priority should be given to bridge suffering greater degrees of damage. These answers were taken into account, however, from past cases, it was found that the lag time in bridge restoration may heavily depend on the importance of the bridge, within the transport network and its rerouting capabilities and redundancies, as well as factors that are beyond the engineering nature of restoration, e.g. recurrence of floods before or during the restoration works.



(a)



(b)

Figure 2. Minimum, maximum and mean values of idle times per damage level for spread (a) and deep (b) foundation.

Table 7 shows the mean and standard deviations of the **cost ratio** per damage level for the two types of foundation, based on elicited information. The results are very much alike with the results obtained for idle time, in the sense that the min values increase for worse bridge damage for deep foundation and the same is observed for the std dev. For example, the restoration of the minor damage on the spread and deep foundation costs approximately 4.6

and 6.0 percent of the reconstruction cost of the entire bridge, whilst severe damage might cost 52 and 58 percent correspondingly.

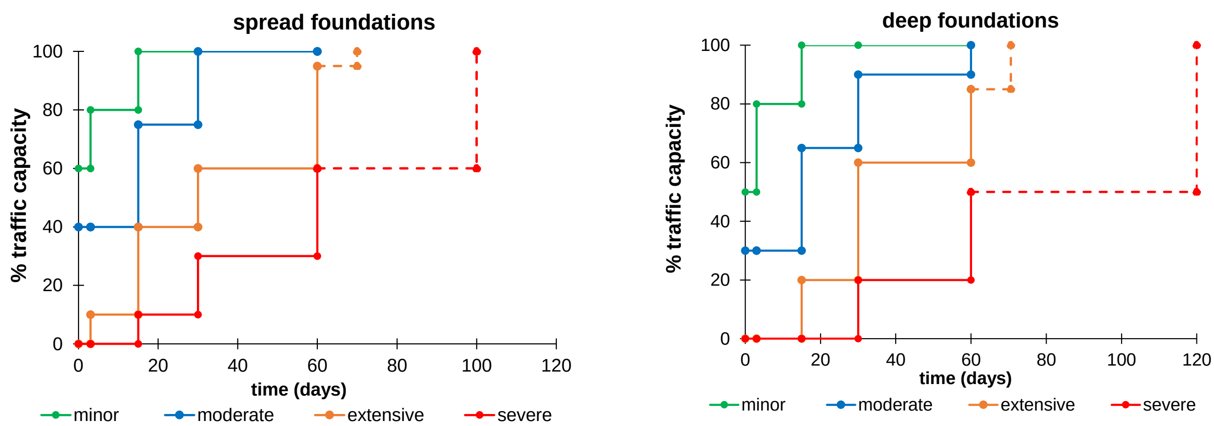
Table 7. Mean and standard deviation (std dev) of the cost ratio per damage level for spread and deep foundations.

	spread foundations		deep foundations	
damage level	**mean**	**std dev**	**mean**	**std dev**
minor	4.6	3.9	6.0	2.5
moderate	12.4	6.7	15.4	6.7
extensive	25.0	8.5	30.4	11.7
severe	52.0	10.0	58.0	17.1

3.3 Traffic reinstatement, capacity restoration and validation

3.3.1 Reinstatement models

Figure 3 shows the reinstatement models that is the traffic capacity evolution after a flood event, which potentially describes the reinstatement of a roadway bridge. The horizontal axis shows the time for the traffic reinstatement in days, whereas the vertical axis shows the reinstatement of traffic capacity, in percentages. Figure 3a shows the results for a flood critical bridge with a spread foundation, whilst Figure 3b shows the results for the bridge with a deep foundation. The continuous lines illustrate the mean values of the elicited opinions - answers of the experts in column 4 of Table 6. The dashed lines include projections based on engineering judgement. From Figure 3a it seems that after a slight, moderate, extensive and severe damage, the functionality is reinstated within 15, 30, 75 and 100 days after the event for bridges with spread foundations, whereas the corresponding recovery of traffic capacity takes 15, 60, 70 and 120 days respectively in bridges with deep foundations, reflecting the fact that traffic capacity is expected to be reinstated a bit slower when foundations include piles. The experts also gave their opinions with regard to the functionality immediately after the flood event for each damage level. The initial traffic capacity after minor damage, for example, was found to have a mean value of 60% for bridges with spread foundations, whereas the functionality was estimated at 50% of the original traffic capacity for the deep foundation. It is also observed that the greater the damage level, the smaller the post-flood traffic capacity. For both foundation types, the post-flood traffic capacity was zero, meaning that the bridge is closed to traffic after extensive and severe damage.



(a) (b)

Figure 3. Reinstatement models illustrating the post-flood gain of the traffic capacity (%) of the bridge for spread (a) and deep (b) foundation (dashed lines is a projection based on judgment).

Figure 4 shows the restoration task prioritisation, dependencies and durations for spread (4a) and deep (4b) foundation per damage level based on the answers of the experts (column 5, Table 6). There has been observed to be a significant deviation among the opinions of experts with regard to the prioritisation of the restoration tasks for all damage levels. Some experts chose a smaller number of tasks, whilst in most cases, the requisite task seems to be R1 (armouring countermeasures and flow-altering), and R12 (rip-rap or gabions for filling scour hole and scour protection). The proposed model considers the common tasks among the answers received, and a balance across tasks and their priorities defined by the experts was achieved based on engineering judgment.

The mean duration and the weighting factors for each task are based on Table 3, while the temporal dependencies and potential overlaps between the tasks were considered, as per the description of section 2.2 and Table 5. The total duration for the restoration of bridges with shallow foundations after floods is estimated equal to 33, 96, 102 and 211 days for minor, moderate, extensive and severe DL respectively. The corresponding durations for the deep foundation are slightly higher at 33, 100, 113 and 211. It is also observed that for minor damage, no differences are expected in the restoration tasks for the spread and deep foundations, hence, the sequence of tasks and expected restoration time is similar. An additional task has been identified for moderate damage in deep foundations, which is related to the strengthening and jacketing of the pile cap (R8), which is not relevant to the shallow foundation. This task will take place after the ground improvement measures (R14) and before the extension of the pile cap (R16). The total restoration time for the spread foundation is slightly smaller for moderate damage compared to the restoration time for deep foundation, i.e. 96 days and 100 days, respectively. This difference is due to task R8, as explained above. Minor damage requires the same tasks and reinstatement duration for both spread and deep foundations, i.e. 33 days. Similarly, for the severe damage, the same restoration time was estimated for both foundation types, because the spread foundation had to be converted to a deep foundation, thus, the restoration time for the spread foundation was found to be equal to the time for restoring the deep foundation, i.e. 211 days.

A sensitivity analysis was performed for deep foundations to identify the influence of the dependency of the duration of each restoration task on the DL (Table 3) on the scheduling of restoration tasks. In particular, weighting factors were all taken equal to 1.0 (i.e. the values in columns 7 to 10 of Table 3), which means that the duration of each restoration task is equal to the mean duration (column 5 in Table 3) across all damage levels. Based on the analysis, it was observed that the bridge reinstatement time is overestimated by 30% for minor (additional 10 days), 13% for moderate (additional 15 days), and 7% for extensive (additional 8 days), while for severe damage no difference is estimated. This is not realistic, as it is explained in section 2.2. A sensitivity analysis was also conducted to understand the influence of the interdependency factors given in Table 5. The results of this sensitivity are given in Table 8, considering full (column 1), partial (column 2) and no dependency (column 3) among restoration tasks, thus corresponding to the minimum, weighted and maximum total expected restoration time. It is understood that the extreme values in columns 1 and 3 are not realistic, as neither all tasks can be implemented simultaneously, nor all tasks are independent.

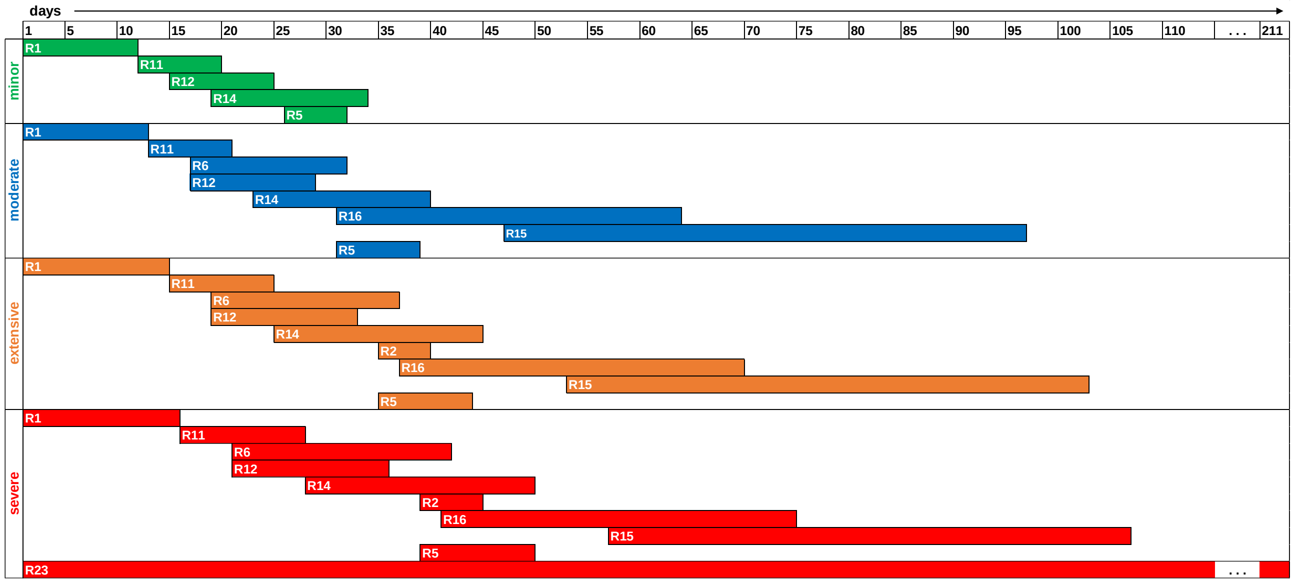
Table 8. Total reinstatement times (days) considering full, partial and no dependency among restoration tasks.

Damage Level	full overlap (fully dependent tasks)	with interdependency factors (table 5)	no overlap (independent tasks)
	(1)	(2)	(3)
		spread foundations	
minor	15	33	50
moderate	50	96	156
extensive	50	102	173
severe	211	211	211
		deep foundations	
minor	15	33	50
moderate	50	100	165.5
extensive	50	113	189
severe	211	211	211

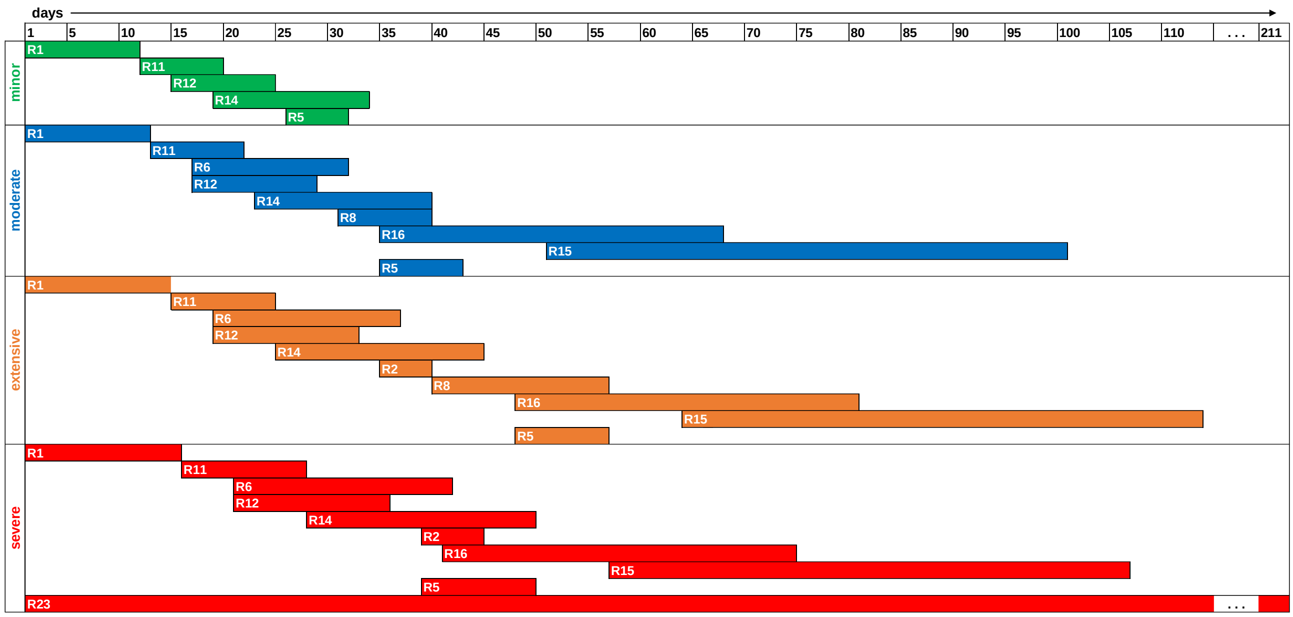
** the values of this table took into account the weighting factors of Table 3. This paper used in column 2*

3.3.2 Capacity restoration models

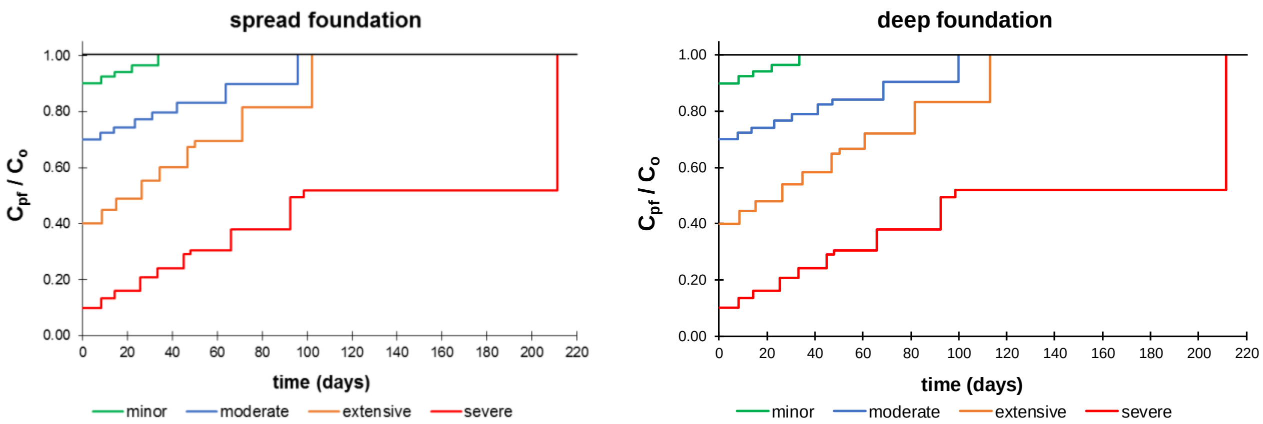
Figure 4c and 4d show the matching stepwise restoration models as per Figure 4a and 4b correspondingly. These figures show the ratio of the post-flood bridge capacity (C_{pf}) over the original capacity (C_o) versus time in days, for spread (4c) and deep (4d) foundations. Both figures take into account the weighting factors and the sequence of the restoration tasks. The C_{pf} of the bridge immediately after the flood event, was taken as 0.9, 0.7, 0.4 and 0.1 for minor, moderate, extensive and severe damage level based on expert judgment, assuming a loss of capacity 10%, 30%, 60% and 90%, respectively. These graphs were the basis for the generation of the restoration models given in Figures 5a and 5b, which are further discussed below. Also, the correlation between the reinstatement of the traffic as per Figure 3 and the restoration of bridge capacity (Figure 4) is discussed in section 3.5.



(a)



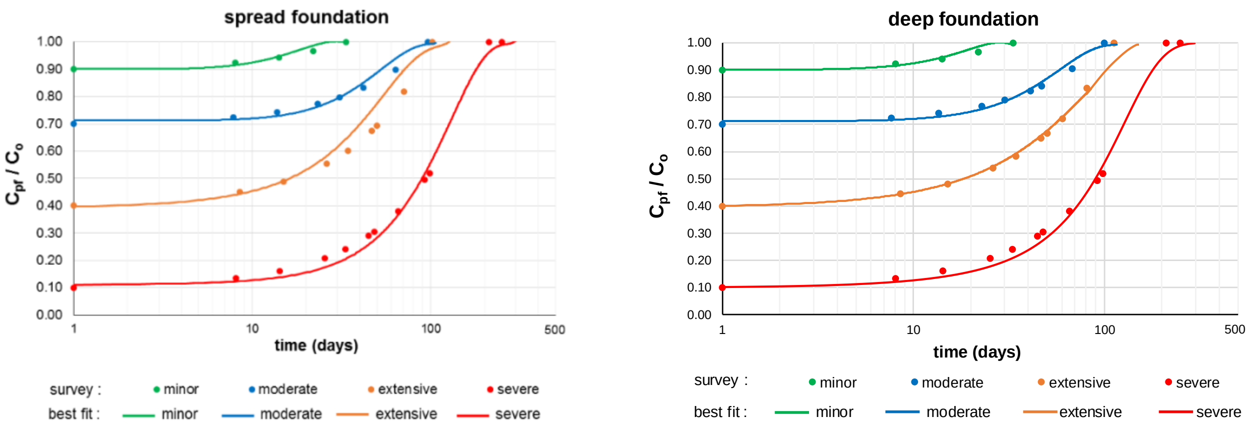
(b)



(c) (d)

Figure 4. The restoration task prioritisation, dependencies and durations for spread (a) and deep (b) foundation per damage level, and stepwise restoration models illustrating the ratio of the post-flood bridge capacity (C_{pf}) over the original capacity (C_o) for spread (c) and deep (d) foundation.

Figure 5 shows the capacity restoration models for flood critical bridges having spread or deep foundation. The results are based on a best-fit approach, for the stepwise restoration graphs of Figure 4 and the same C_{pf} values at time t=1 day were used. A polynomial regression curve was used in that case as it was found to lead to minimal errors, whilst it has the benefit of a continuous representation of the evolution of C_{pf} / C_o, thus it can be used for a portfolio of bridges for simulation purposes.



(a) (b)

Figure 5. Optimised restoration models (best fit) for post-flood bridge capacity (C_{pf}) over original capacity (C_o) for spread (a) and deep (b) foundations.

3.4 Validation of results

3.4.1 Evidence from literature

Based on an extensive bridge inventory after the province of Manitoba Canada floods in the spring of 2011 and summer of 2014 (Monnier et al. 2015), it was found that bridges suffered damage mainly due to scour of their foundations. Bridges had remained fully functional as the condition of the superstructure allowed fully operational bridges, apart from one on PTH 41 over the Assiniboine River, where the functionality was reduced by 50%, i.e. reduction of traffic lanes from two to one. For example, the bridge over the Portage diversion channel experienced extensive scour, while no tilting or cracking of its piers was observed, with a good overall condition of its deck and substructure. The lag time was more than six months (design took 45 days), whilst the duration of the restoration was approximately one month, which is similar to the restoration time for minor damage shown in Figure 4a and 4b. The bridge on TCH 1W over Assiniboine river also experienced severe scour and its restoration time was approximately five months with an interim disruption of three months due to floods. The bridge on PTH 10 over the Souris river exhibited minor damage based on the description of this paper, while its restoration took three months, including the construction of a new deep foundation for one pier. This restoration strategy was decided to safeguard the lateral stability of its 12m high piers for preventing the risk of future failure due to scour. Hence, this duration is similar to the restoration of extensive damage in Figure 4a, which includes the installation of a deep foundation for a scoured bridge with spread foundation, i.e. 102 days. In extreme cases of bridge foundation damage, restoration may take up to two years (e.g. bridge on PTH 2 over the Souris River), yet, the largest part of this time is idle time, whilst the actual construction time was approximately 90 days including a new deep foundation as per the case above. The extensive idle time is usually due to site investigations (e.g. bathymetric, topographic and subsurface survey) as well as recurrences of floods.

A second verification of the results was attempted with the closure times provided in Misra et al. (2020), which was based on expert elicitation. The latter described three damage levels, i.e. BS1 - scour at abutment leading to piles being exposed, assuming piles of length 40 ft (~15 m) and depth of scour to be about 5 ft (~1.5 m); BS2 - scour at column base leading to exposed foundation, assuming piles of length 50 ft (~1.5 m) and depth of scour to be about 3 ft (~0.9 m); and BS3 - scouring leading to settlement at pier. The mean reinstatement times were reported to be 15.7, 12.6 and 158.1 days for BS1, BS2 and BS3 correspondingly. The reinstatement times for BS1 and BS2 are very similar. BS2 matches the description of minor damage level illustrated in Table 1 under deep foundation, because no substantial settlement and/or cracking of the structural component is observed. The latter yielded a mean reinstatement time of 33 days, which is same order of magnitude with the restoration of BS2, i.e. 12.6 days. The difference is attributed to the different description of damage provided to the experts and the variability of practices across the world. BS3 falls between the descriptions of extensive and severe damage levels of the present paper, hence, the mean reinstatement time, is between 102 and 211 days, i.e. an average of 156.5 days, which is very similar to the 158.1 days for BS3. Moreover, both this paper and the study of Misra et al. (2020) concluded that the mean reinstatement (closure) time is much smaller than the mean restoration time (gain of capacity after repair). Indeed, this paper found that the reinstatement time can be half the time required for restoring the bridge.

3.4.2 Evidence from on-site investigation

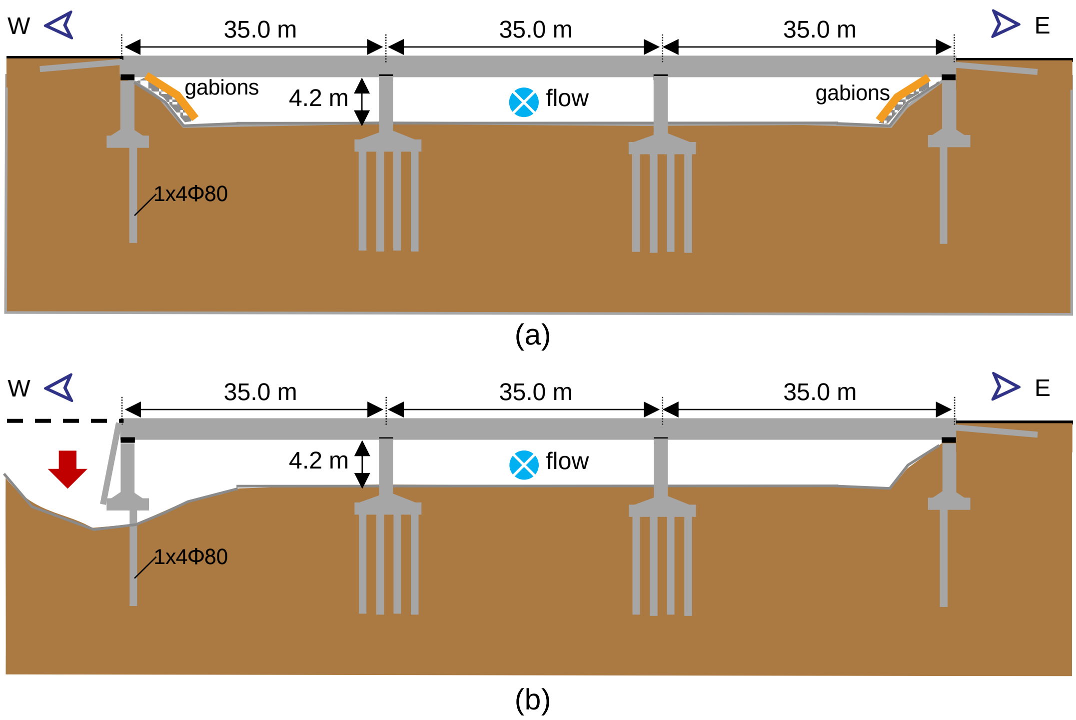
On 17 September 2020, the Mediterranean hurricane “Ianos” struck Greece affecting a great part of the country. In the most impacted areas, the amount of precipitation was among the highest ever recorded, substantially exceeding the mean annual precipitation. Numerous infrastructure failures took place as a consequence of the associated flooding as reported in detail in Zekkos et al. (2020). Particularly pronounced was the damage to bridges located in the mountainous regions west of the city of Karditsa (central Greece) and especially at the town of Mouzaki, where extensive to severe damage of at least five bridges, within a radius of 3 km, caused a major disruption of the transportation network.

This extreme event provided important evidence of scour-induced bridge damage and recovery efforts. One particular case, discussed in the following, serves well as reference for validation of our models, which has significant similarities (Figure 6a) with the benchmark bridge of this paper (Figure 1). It involves a relatively modern motorway crossing of Pamisos river at the very centre of Mouzaki town (coordinates of location: 39.427341667°N; 21.667275000°E). It is a three-span reinforced concrete structure with a continuous box-girder deck, which is connected to its piers through sliding bearings while is simply supported upon the abutments. Both the abutments and the piers are supported on pile groups. The bridge suffered substantial damage, i.e. extensive on the west abutment (Figure 6b) and severe on the backfill soil according to the classification of damage in Annex A. The backfill was completely washed away causing the loss of support and collapse of the approach slab and the road pavement (Figure 6c). An average height of 1.9 m of the foundation piles was exposed (Figure 6d) as a result of scouring.

We have been monitoring restoration actions that took place on site since their beginning and summarise them in Table 9, also showing the progress of the bridge reinstatement. The bridge was closed for a total of 10 days, during which restoration tasks related to temporary flow altering (R1) and debris removal (R13) took place. Partial opening to traffic after day 10 was achieved thanks to rebuilding of the backfill (R20) and construction of a temporary approach road surface after filling the hole. It is worth noting that the approach road was permanently restored later, after day 54, with the construction of a reinforced concrete approach slab. The strategy of splitting R20 tasks in two parts was adopted for the purpose of allowing temporarily undisturbed opening of the motorway to traffic as soon as possible after the event. Enhancement of the abutment foundation and filling of the scour hole with gabions (R12) took place after the partial reinstatement of the bridge. A photograph captured on day 25 is shown in Figure 6e.

The duration of all restoration tasks that took place, i.e. R1, R13, R20, R12, and R11, compare well with the estimated minimum durations suggested in Table 3. This is due to the concurrence of two importance factors, related to the absence of suitable diversion routes and the unacceptable community severance as a result of prolonged closure of the bridge. Based on further information that was elicited by the engineer in charge, great effort was placed on minimising idle time, for mitigating the disruption of the heavily impacted network, which is relating to adverse weather conditions and lack of resources. Therefore, the idle time was 22 days in total, split in intervals of 2, 11, 9 days (Table 9), which is between the mean values of extensive (18 days) and severe damage (28 days) according to Figure 2b, yet, it is recognised that the figure refers to deep foundations.

The traffic of the bridge was reinstated 54 days after the event, while the restoration tasks were completed on day 65, including the idle time. The differences between Figure 3b (70 days instead of 54) and Figure 4b (113 days instead of 65) for extensive damage of deep foundations, are attributed to: a) the bridge importance which accelerated the restoration, b) the nature of the damage which, albeit extensive, it did not includ structural failure of the abutment wall or its piles, and as such, there was no need for task R15 (with a mean duration of approximately 50 days). Yet, the durations of all individual tasks were between the minimum and maximum values estimated by the experts on Table 3.



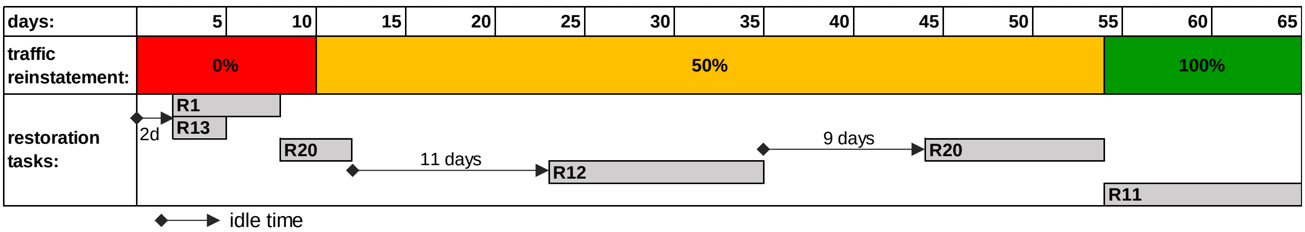
(c)

(d)

(e)

Figure 6. Damage due to scour and restoration of a road bridge in the town of Mouzaki, central Greece, after hurricane "Ianos". Schematic of the original bridge geometry (a), and the abutment damage (b). Photographs of the collapsed road segment (aerial c), the exposed pile group supporting the west abutment (d), and ongoing restoration works (R12: gabions) 26 days after the event (e).

Table 9. Restoration tasks and traffic reinstatement of the road bridge at Mouzaki (Greece).



3.5 Correlation between reinstatement and restoration

Traffic loads represent only a very small portion of the total bridge load (usually represented less than 5%) as a result, these cases, were dealt with fully open or 50% traffic capacity even though the foundation experienced extensive and/or severe damage in some cases. It is believed that the decision to maintain fully /partially the bridges operational, was related to the fact the superstructure did not exhibit a concerning degradation of capacity. Yet, in some cases, stakeholders may close a bridge to traffic if less critical event is observed e.g. if the inundation depth exceeds a certain threshold, leading to an overtopping risk and thus potentially leading to fatalities due to overtopping rather than a bridge failure. Thus, the bridge closure to traffic is strongly case-dependent and there is a number of factors that define the rapidity of recovery such as the transport network redundancies, engineering and non-engineering parameters, e.g. accessibility, type of river (calm, torrential, low/high flow), and the emergency assigned to the repair with experts stating that "*…you put the means into it, you bring in the Centre National des Ponts de Secours (CNPS), you get rid of the market code to place direct orders with companies, you rent an Antonov with €500,000 to transport metropolitan equipment to French Guiana to save the Larivot bridge...*". However, information obtained from stakeholders in the UK (Network Rail) indicated that bridges might close to traffic when inundation depth exceeds certain thresholds, even though the asset might not have any indication of damage. The questionnaire allowed the correlation between the traffic reinstatement and the restoration time and it was found that on average the latter one is 1.8 to 2.2 times greater than the reinstatement time, which demonstrates and aims for minimising the indirect costs due to closure.

3.6 Resilience of flood-critical bridges accounting for climate change

Climate change is also expected to have an impact on the frequency and/or magnitude of flood events and thus on the restoration of bridges. Even if annual mean precipitation trends may reduce over time, heavy rainfall events can intensify at a regional level (Kendon et al. 2014). Understanding the mechanisms of extreme precipitation and its hydro-meteorological connection with flooding, especially within the context of climate change, is essential towards mitigating the effects of floods on bridge structures (Duan et al. 2017) and their restoration and reinstatement tasks. The majority of the studies investigating the effects of climate change on bridge scour have looked at the problem at a national bridge stock level through the use of simple relationships between the hazard (flood flow) and bridge vulnerability/risk (Nemry and Demirel 2012, Wright et al. 2012, HR Wallingford 2014, Dawson et al. 2018). These studies assessed how the risk profile distribution of bridge portfolios may be expected to change under different climate change scenarios. However, the change in scouring risk related to an increase in flood flows (projected due to climate change) may not be a straightforward relationship. The latter is due to the fact that beyond a threshold, scour depth does not necessarily increase in line with an increase in flow (Lamb et al. 2017). Yet, the challenge remains, especially for older bridges with unknown foundations and not clearly specified design standards; such bridges may be more sensitive to the risk of increased flooding in a future climate, including the associated great uncertainties (Dikanski et al. 2018). More recent studies have focused on quantifying in more detail the effects of climate change on risk and resilience of bridges and transport networks (Yang and Frangopol 2019, Devendiran et al. 2021). By using a multi-hazard framework including floods and earthquakes they found that the consideration of different climate change scenarios resulted in significant rise in risk, up to 21%, and drop in resilience (14%) of typical bridges, when compared to no climate change scenario, at a specific seismic hazard level. The study by Yang and Frangopol (2019) assessed the scour risk on a regional bridge network and showed a potential maximum 50% increase in risk by the 2100s considering climate change as compared to a baseline scenario, without climate change.

Climate change adaptation options for scour-critical bridges may include structural and non-structural measures. In terms of structural measures, options include strengthening existing bridges against scour. On the other hand, non-structural adaptation measures include updating of codes and standards to accommodate the potential effect of climate change and the use of monitoring techniques to more reliably understand the effects of floods on the scour development. It should be noted that the choice of the adaptation measures to be followed should be clearly based on quantifying the costs-benefits involved as well as the long-term risks that need to be captured. A number of such frameworks have been recently been developed and can prove useful towards climate change adaptation of scour-critical bridges (Kallias and Imam 2016, Yang and Frangopol 2019, Liu et al 2020). These are matters that need further research, but can be simplistically taken into account by considering adjustment factors to account for longer restoration, reinstatement and/or adaptation times into the proposed restoration models.

4 Conclusions

This paper provides a set of reinstatement and restoration models for bridges with shallow and deep pile foundations that reflect the recovery of traffic and capacity of typical reinforced concrete bridges. The results of this study are based on findings from the literature, expert elicitation, based on a questionnaire, and engineering judgement. The research aims at filling a fundamental gap in the current state of the art, namely the complete absence of recovery and resilience models for flood critical bridges. The research on the recovery of bridges after floods revealed the following:

The opinions of the experts who completed the questionnaire and provided narratives and comments were found to have great deviations and their responses were found to be highly case-dependent. The same was observed during the validation of recovery models based on published research and reports of past events. It was also found that bridge operability is of utmost importance, the main reason being the high value of indirect costs, which are an order of magnitude higher than direct restoration costs. This was also reflected by the expert elicitation questionnaire, where the duration of the reinstatement of bridge traffic was approximately half the duration of the restoration of bridge capacity.

It was found that the opinions of the experts regarding the post-flood idle (lag) time differ significantly. Some experts believe that more serious damage of flood-critical bridges is been dealt with quicker, while slight damage to bridges after floods may have longer lag times because the bridge can remain functional and open to traffic. Large deviations in idle time and restoration strategies and approaches were also observed in the literature from which past events were vetted and documented. In regard to the restoration times following bridge flood damage, the literature showed little dependence on the damage level, with restoration times generally being swift. Results based on the questionnaires indicated a correlation with the literature, with extensive and severe damage being dealt with more slowly than slight and moderate ones. The selection of prioritisation of the restoration tasks also indicated a technical and temporal dependency between subsequent restoration tasks, which was taken into account with the execution of dependency factors. In addition, based on the results of the elicitation questionnaire and engineering judgement, sets of damage level dependent adjustment factors were defined to adjust the duration of the tasks.

This study has some limitations as the experts who took part in the survey were from Europe. The repair duration should also take into account the effects of operators' policies and available resources, the bridge importance as well as global effects, such as the financial growth of developed or developing countries. If restoration models are required in such cases, appropriate adjustment factors can be introduced to parameterise the proposed models to reflect throughout the life of the asset the variabilities in idle times and restoration strategies, which describe the restoration path and rapidity. Updating of restoration models can be achieved by incorporating new responses from experts, evidence from past and new cases documented by bridge owners in different regions as well as data and evidence that can be obtained by digital means e.g. satellite imagery, lidar and photogrammetric methods. Currently there is very little research available on the fragility of bridges exposed to floods, scour and hydraulic forces, thus, bridge damage assessment is of high aleatory and epistemic uncertainty, which propagates into the recovery process. Therefore, uncertainties related to the restoration tasks and their durations are greater and appropriate treatment by deploying streamlined methods, e.g. Monte Carlo sampling or machine learning techniques, would be beneficial.

This research endeavour will continue to cover in the future matters relevant to the recovery of all bridge components (see Annex), assuming a series or series-parallel model of DL, bridges with a larger number of spans and/or of different materials, the correlation with the resilience of the network, the influence of climate change, including adaptation and projections.

Acknowledgements

We are grateful to the experts provided their opinions. The elicitation methodology and the research findings given in this paper are not attributable to any individual and the subsequent interpretations presented are only reflecting the opinions of the authors.

Dr Sotirios A Argyroudis would like to acknowledge the support of the European Commission under the H2020-Marie Skłodowska-Curie Research Grants Scheme MSCA-IF-2016 (grant agreement No 746298: TRANSRISK-Vulnerability and risk assessment of transportation systems of assets exposed to geo-hazards).

Dr Marianna Loli would like to acknowledge the support of the European Union H2020-Marie Skłodowska-Curie Research Grants Scheme MSCA-IF-2019 (grant agreement No 895432: ReBounce-Integrated resilience assessment of bridges and transport networks exposed to hydraulic hazards).

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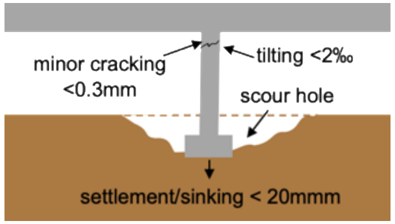
Annex A: Hydraulic induced damage to bridge components

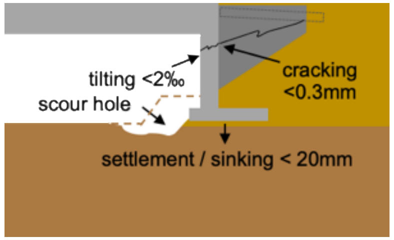
<table>
<tr><th>damage level (DL)</th><th>pier</th><th>abutments & wingwalls</th></tr>
<tr><td>minor</td><td>

- Pier settlement/sinking: <20 mm
- Pier tilting: <2‰
- Minor spalling at the pier (damage requires no more than cosmetic repair), cracking width: <0.3mm



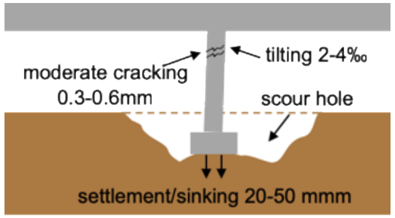
</td><td>

- Abutment & wingwalls settlement/sinking: <20 mm
- Abutment & wingwalls tilting: <2‰
- Minor spalling at the abutment & wingwalls (damage requires no more than cosmetic repair), cracking width: <0.3mm



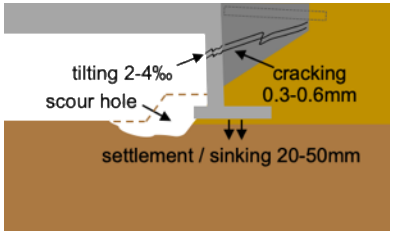
</td></tr>
<tr><td>moderate</td><td>

- Pier settlement/sinking: 20-50 mm
- Pier tilting: 2-4‰
- Moderate shear cracking and spalling (pier structurally still sound), cracking width: 0.3-0.6mm



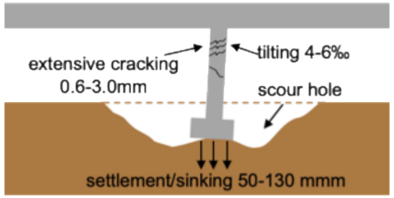
</td><td>

- Abutment & wingwalls settlement/sinking: 20-50 mm
- Abutment & wingwalls tilting: 2-4‰
- Moderate shear cracking and spalling (abutment structurally still sound), cracking width: 0.3-0.6mm



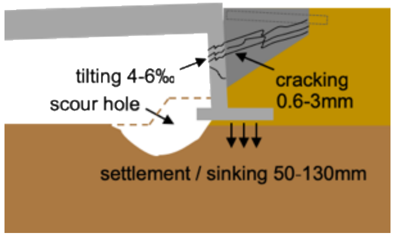
</td></tr>
<tr><td>extensive</td><td>

- Pier settlement/sinking: 50-130 mm
- Pier tilting: 4-6‰
- Pier degrading without collapse – flexural and/or shear extensive damage (pier structurally unsafe), cracking width: 0.6-3mm
- Reinforcement yielding



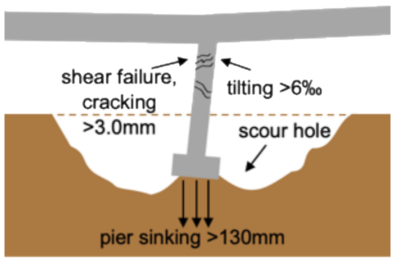
</td><td>

- Abutment & wingwalls settlement/sinking: 50-130 mm
- Abutment & wingwalls tilting: 4-6‰
- Abutment & wingwalls degrading without collapse – flexural and/or shear extensive damage (abutment structurally unsafe), cracking width: 0.6-3mm
- Reinforcement yielding



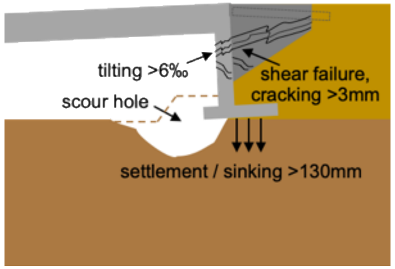
</td></tr>
<tr><td>severe</td><td>

- Pier settlement/sinking: >130 mm
- Pier tilting: >6‰
- Flexural and/or shear failure and/or overturning of the pier, cracking width: >3mm
- Reinforcement failure

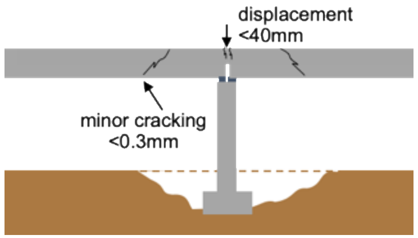
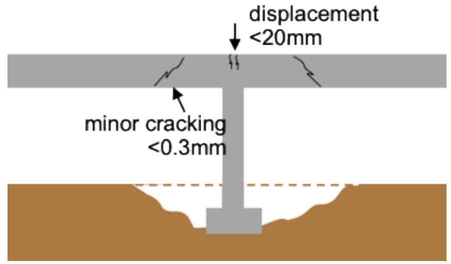
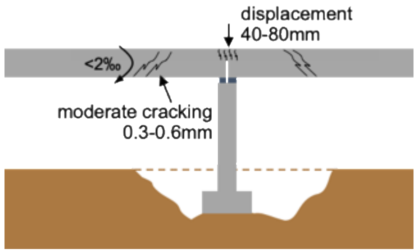
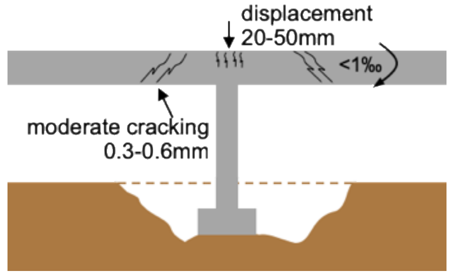
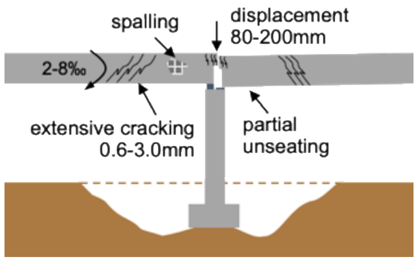
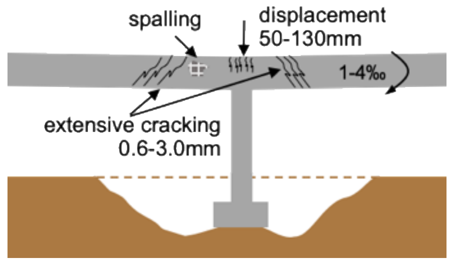
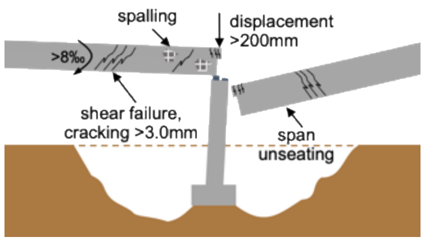
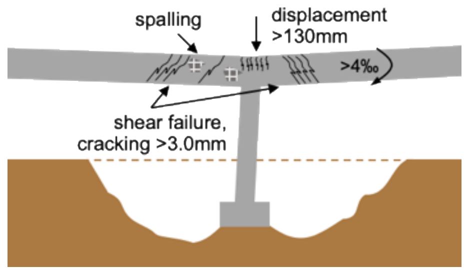


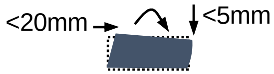
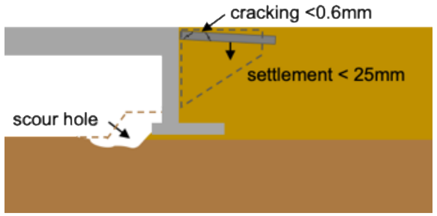
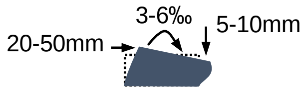
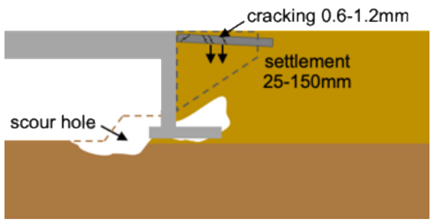
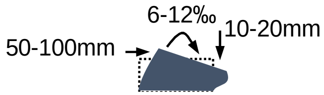
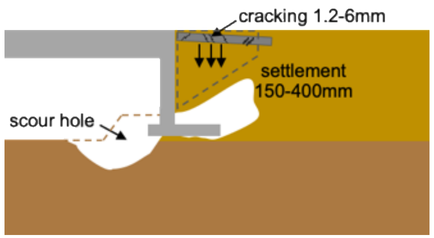
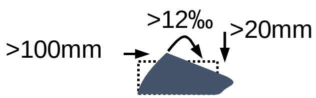
</td><td>

- Abutment & wingwalls settlement/sinking: >130 mm
- Abutment & wingwalls tilting: >6‰
- Flexural and/or shear failure and/or overturning of the abutment & wingwalls, cracking width: >3mm
- Reinforcement failure



</td></tr>
</table>

<table>
<tr><th>damage level (DL)</th><th colspan="2">simply-supported deck</th><th colspan="2">continuous deck</th></tr>
<tr><td>minor</td><td>- Minor spalling and cracking of the deck, cracking width: <0.3mm
- Vertical and/or horizontal deflections/displacements of the deck: <40mm</td><td></td><td>- Minor spalling and cracking of the deck, cracking width: < 0.3mm
- Vertical and/or horizontal deflections/displacements of the deck: <20mm</td><td></td></tr>
<tr><td>moderate</td><td>- Moderate spalling and cracking of the deck, cracking width: 0.3-0.6mm
- Vertical and/or horizontal deflections/displacements of the deck: 40-80mm
- Twisting/rotation of the deck about longitudinal axis: <2‰</td><td></td><td>- Moderate spalling and cracking of the deck, cracking width: 0.3-0.6mm
- Vertical and/or horizontal deflections/displacements of the deck: 20-50mm
- Twisting/rotation of the deck about longitudinal axis: <1‰</td><td></td></tr>
<tr><td>extensive</td><td>- Extensive spalling and cracking of the deck, cracking width: 0.6-3mm
- Vertical and/or horizontal deflections/displacements of the deck: 80-200mm
- Twisting/rotation of the deck about longitudinal axis: 2-8‰
- Reinforcement or prestressed steel yields in one location
- Span (partial) unseating at one support</td><td></td><td>- Extensive spalling and cracking of the deck, cracking width: 0.6-3mm
- Vertical and/or horizontal deflections/displacements of the deck: 50-130mm
- Twisting/rotation of the deck about longitudinal axis: 1-4‰
- Reinforcement or prestressed steel yields in one location and/or hinge formation at one location</td><td></td></tr>
<tr><td>severe</td><td>- Excessive spalling and cracking of the deck, cracking width: >3mm
- Vertical and/or horizontal deflections/displacements >2000mm
- Twisting/rotation of the deck about longitudinal axis: >8‰
- Reinforcement or prestressed steel fails in multiple locations
- Span unseating</td><td></td><td>- Excessive spalling and cracking of the deck, cracking width: >3mm
- Vertical and/or horizontal deflections/displacements >130mm
- Twisting/rotation of the deck about longitudinal axis: >4‰
- Reinforcement or prestressed steel yields in multiple locations and/or span collapses</td><td></td></tr>
</table>

damage level (DL)	bearings	backfill and approach slab
minor	- Bearing shear displacement: <20mm - Bearing rotation: <3‰ - Bearing axial displacement: <5mm 	- Backfill and approach slab settlement: <25mm - Minor cracking of the approach slab: <0.6mm 
moderate	- Bearing shear displacement: 20-50mm - Bearing rotation: 3-6‰ - Bearing axial displacement: 5-10mm 	- Backfill and approach slab settlement: 25-150mm - Moderate cracking of the approach slab: 0.6-1.2mm - Moderate scour or wash out of the backfill: ~10% loss of the backfill material (i.e. volume) 
extensive	- Bearing shear displacement: 50-100mm - Bearing rotation: 6-12‰ - Bearing axial displacement: 10-20mm 	- Backfill and approach slab settlement: 150-400 mm - Extensive cracking of the approach slab: 1.2-6mm - Extensive scour or wash out of the backfill: ~25% loss of the backfill material (i.e. volume) 
severe	- Bearing shear displacement: >100mm - Bearing rotation: >12‰ - Bearing axial displacement: >20mm 	- Backfill and approach slab settlement: > 400mm - Excessive cracking of the approach slab: >6mm - Excessive scour or wash out of the backfill: >25% loss of the backfill material (i.e. volume)