University of Surrey
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Vulnerability, risk and resilience assessment of bridges to hydraulic hazards

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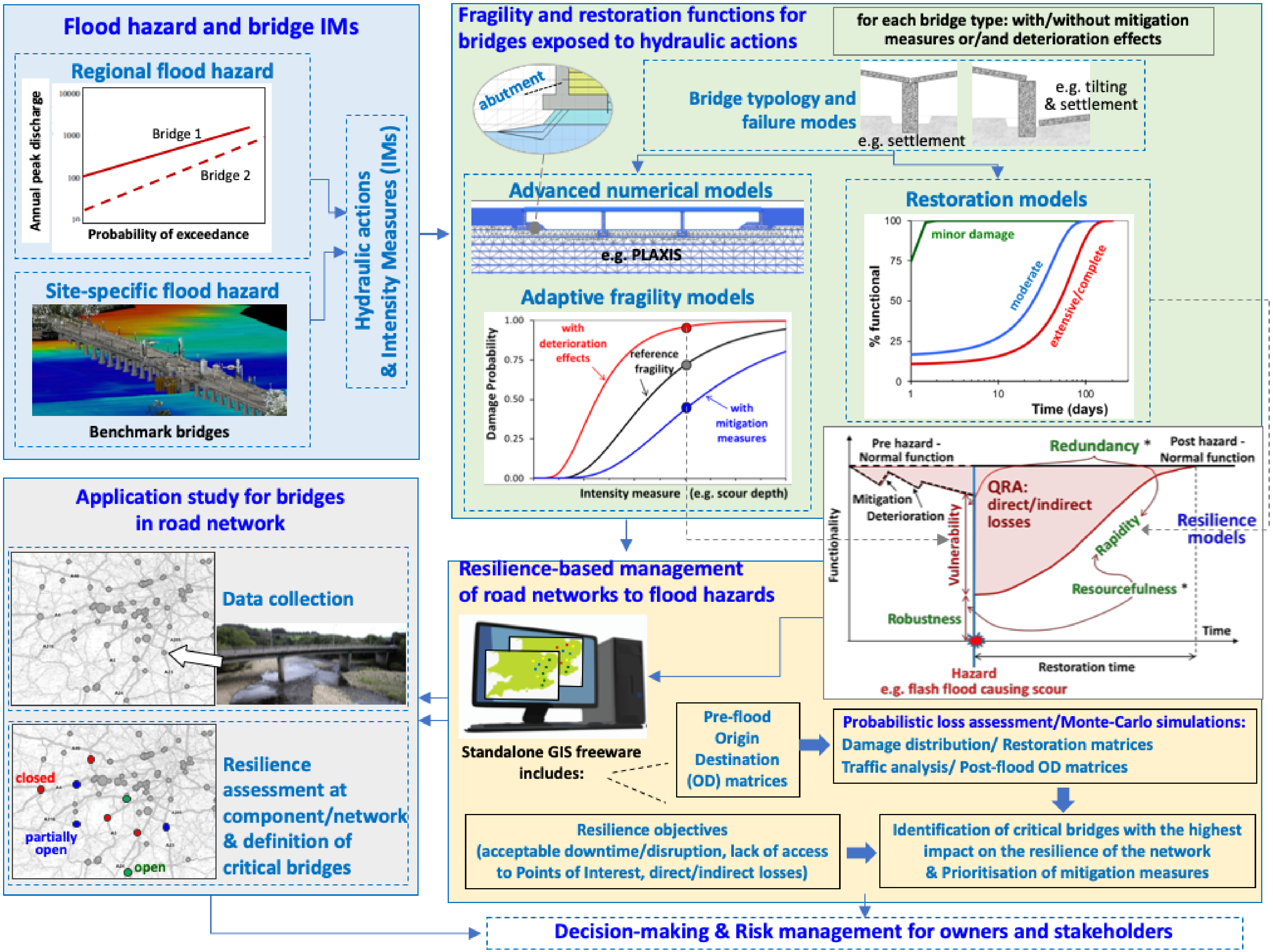
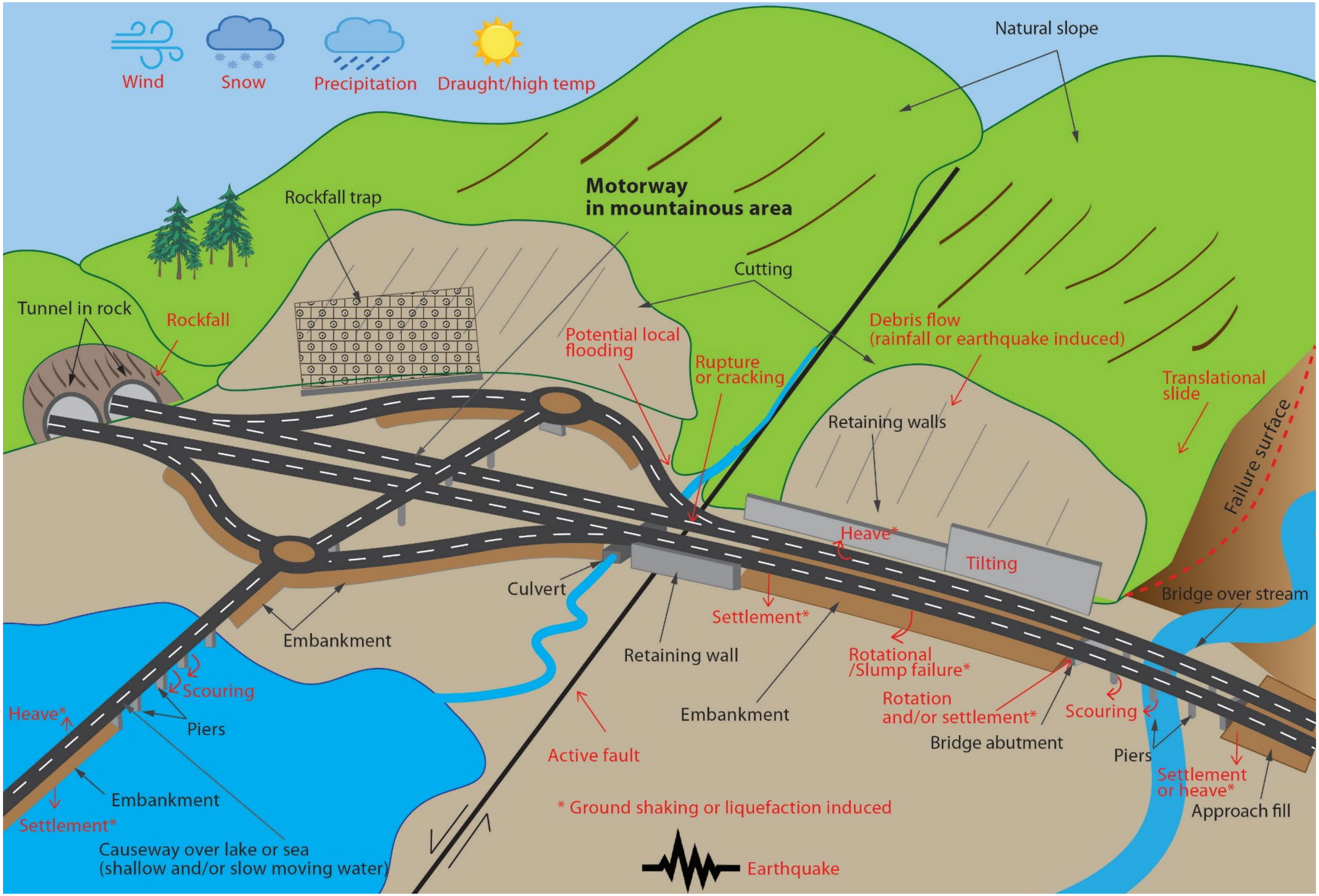
Quantitative risk and resilience assessment



* Redundancy and Resourcefulness enhance Rapidity and Robustness and thus reduce the Vulnerability of bridges and transportation networks

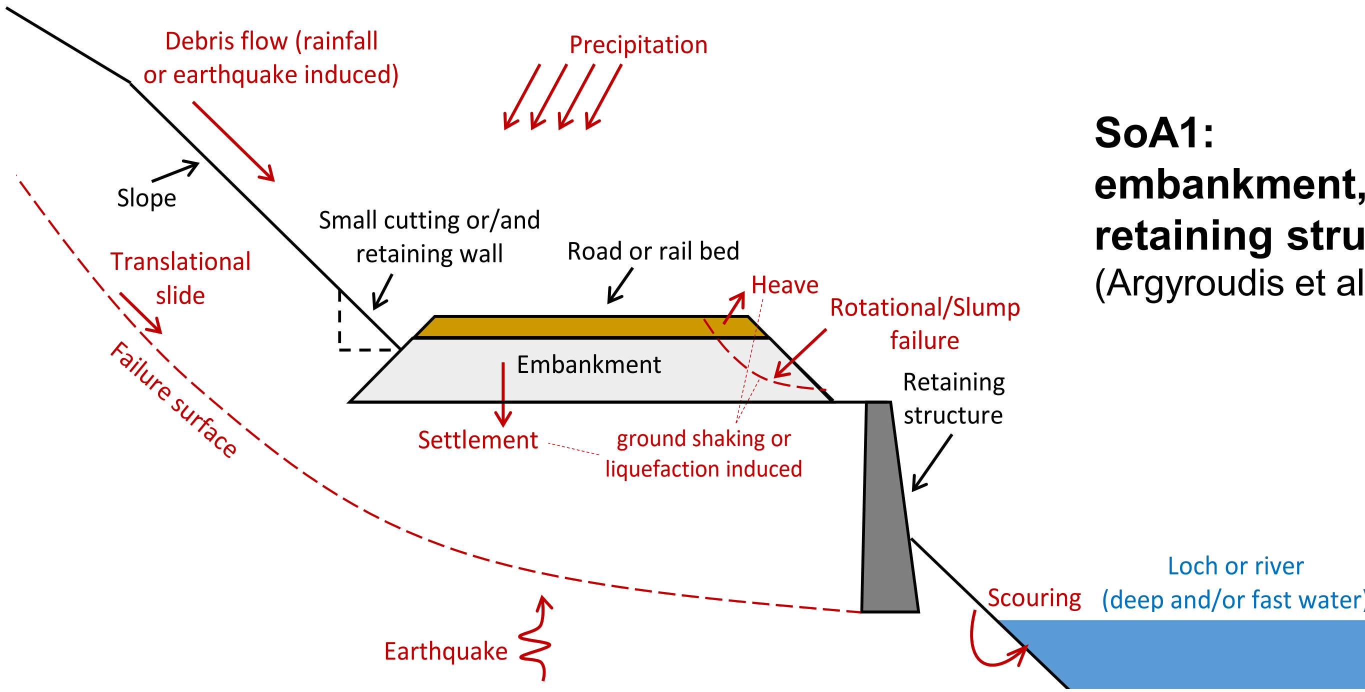
Transport Systems of Assets (SoA) in diverse ecosystems



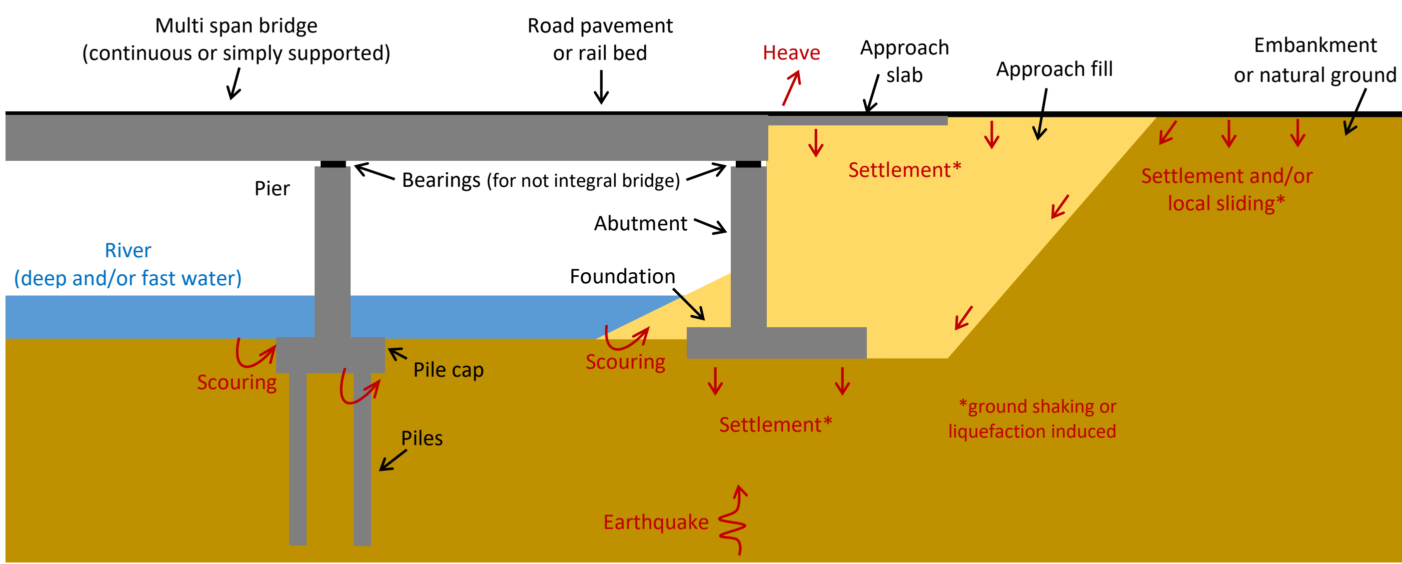
Motorways in mountainous areas

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

Geo-hazard effects to representative transport SoA



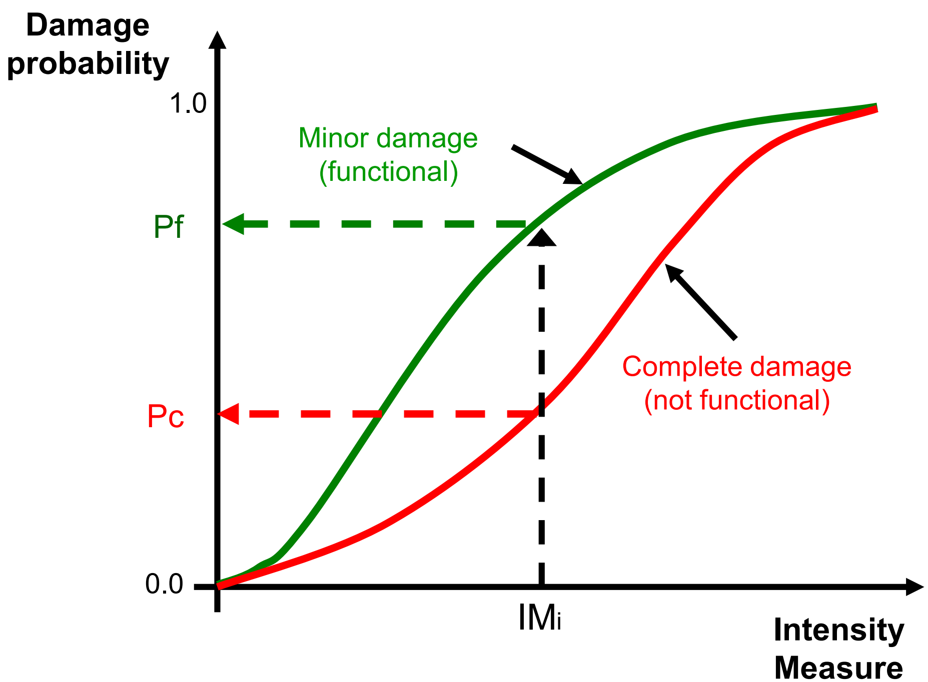
SoA1:
embankment, slope, retaining structure
(Argyroudis et al. 2018b)



SoA2:
bridge, abutment, embankment
(Argyroudis et al 2018a)

Fragility curves

They describe the probability of exceeding a certain limit state (e.g. minor, moderate, extensive damage, collapse) as a function of a hazard intensity measure (e.g. PGA for earthquake, permanent ground displacement for ground movements, peak water discharge for flooding).

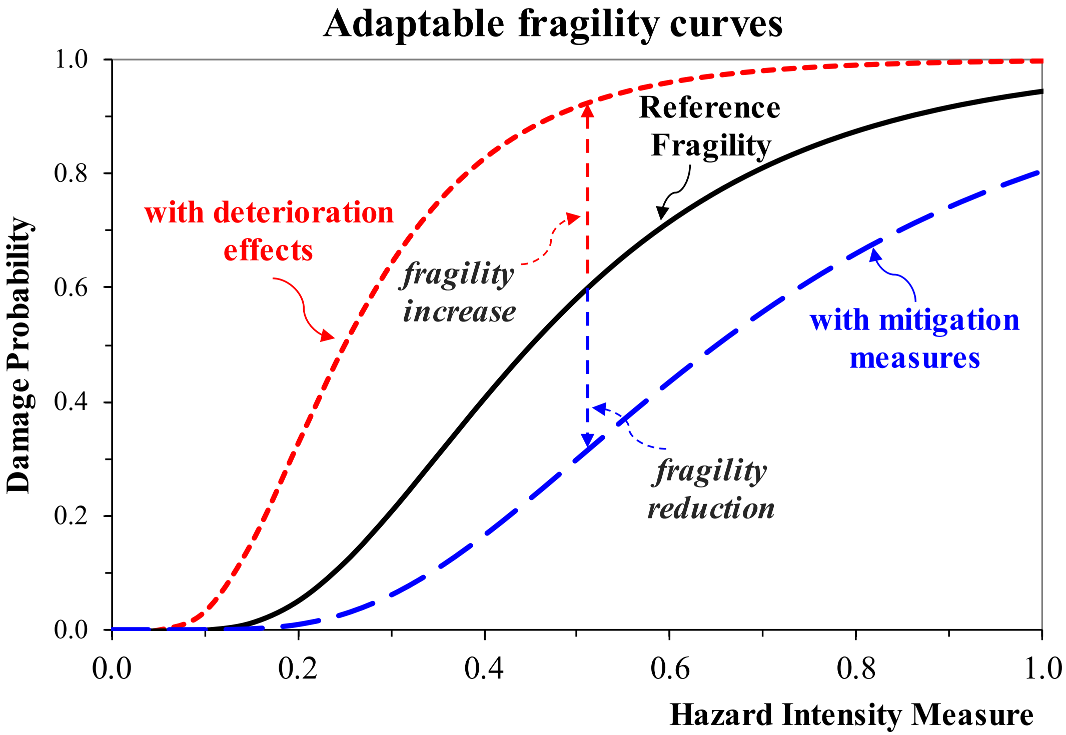


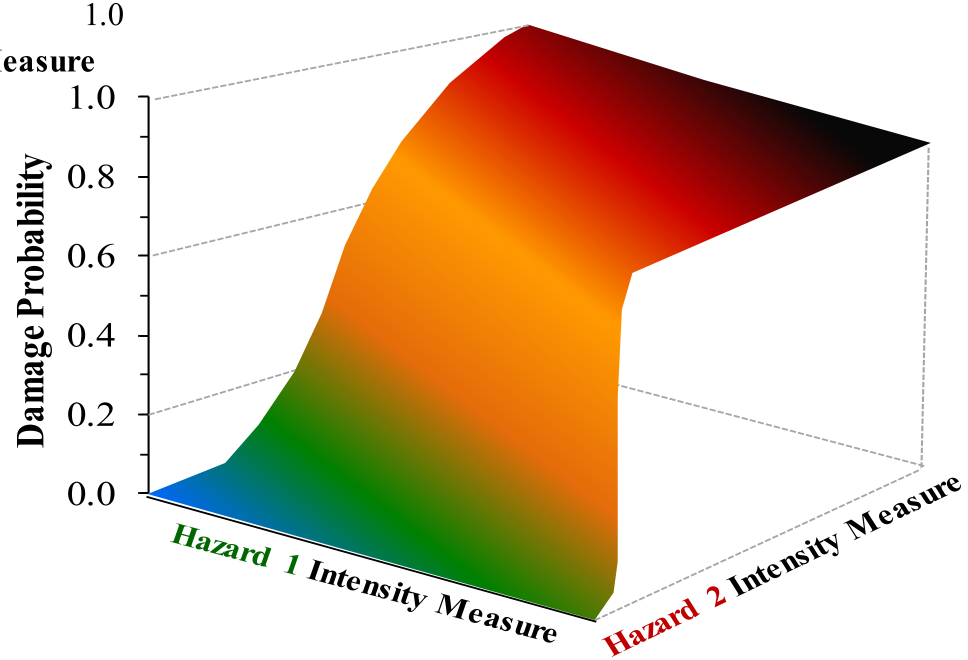
Commonly or typically they are expressed with lognormal functions

Developed with different approaches:

- Empirical (observed data)
- Expert judgment (elicitation data)
- Analytical (numerical simulation)
- Hybrid (combination)

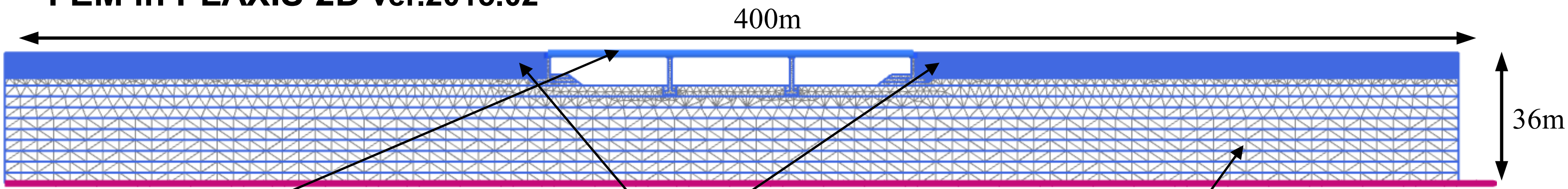
Fragility models





Numerical fragility model for integral bridge-backfill system

FEM in PLAXIS 2D ver.2015.02



Bridge

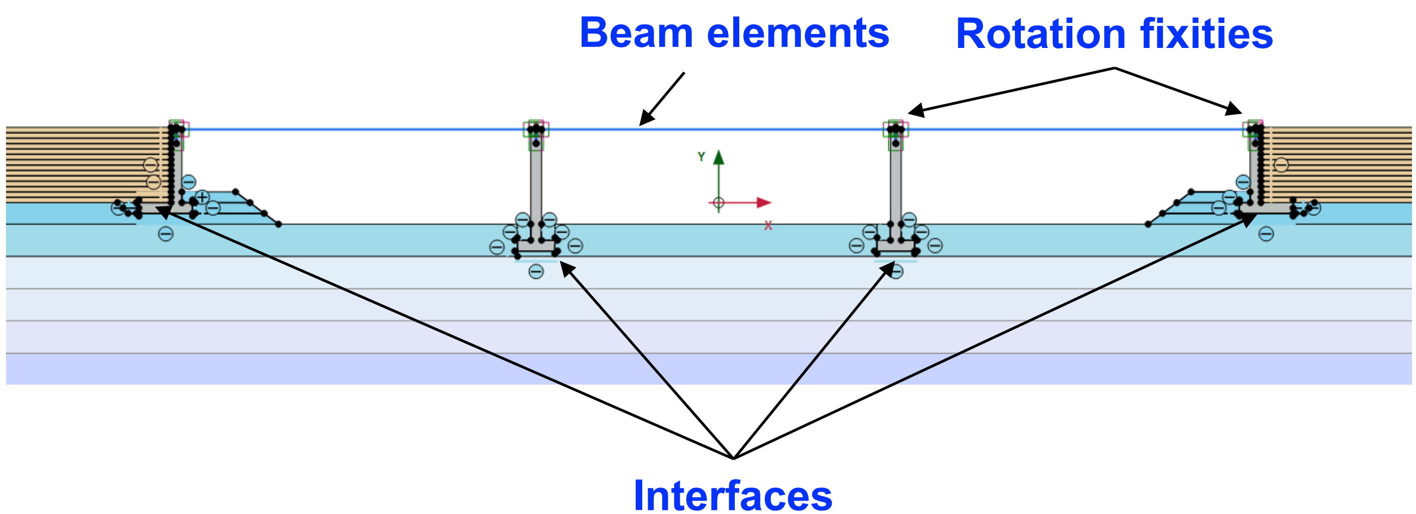
- 3-span pre-stressed concrete bridge
- length: 100.5m
- deck: box girder
- width: 13.5m
- abutment height: 8m

Backfills

- well compacted sand
- φ = 42°, γ= 18.5 kN/m^3

Foundation soil

- stiff clay type B (EC8)
- γ=19.5 kN/m^3
- Mohr-Coulomb model



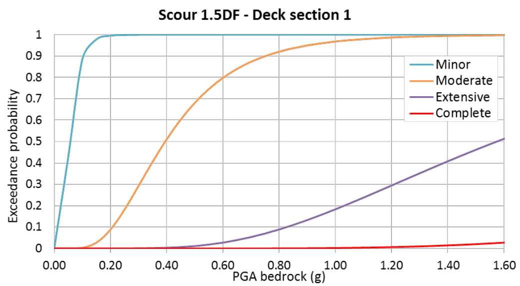
Argyroudis S, Mitoulis S, Kaynia AM, Winter MG (2018b). Fragility assessment of transportation infrastructure systems subjected to earthquakes. Geotechnical Earthquake Engineering and Soil Dynamics V, June 10-13, Austin, Texas, USA, [Geotechnical Special Publication] (GSP 292), pp 174-183

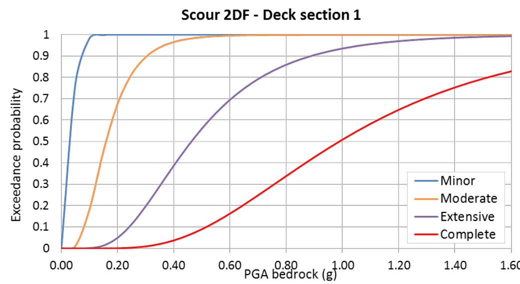
Numerical fragility curves for integral bridge

1.5 Df

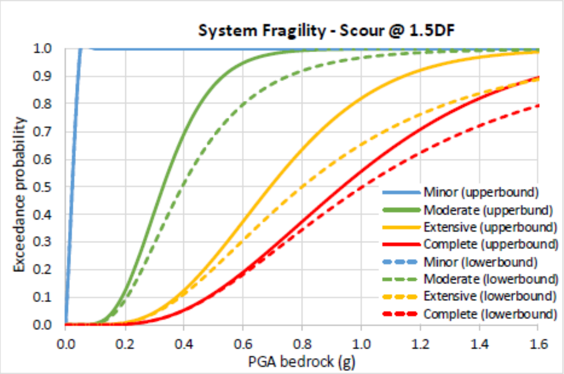
2.0 Df

Deck

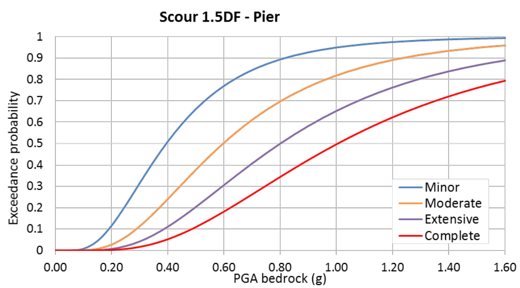




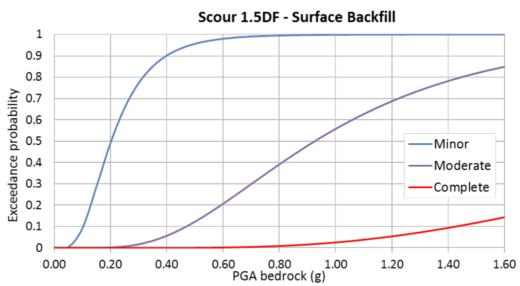
System fragility

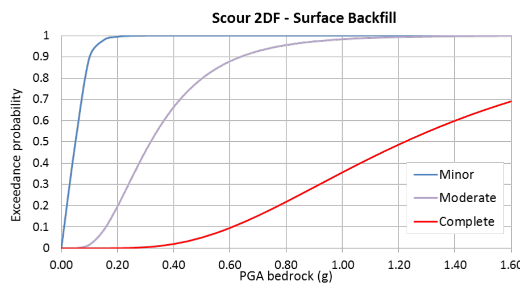


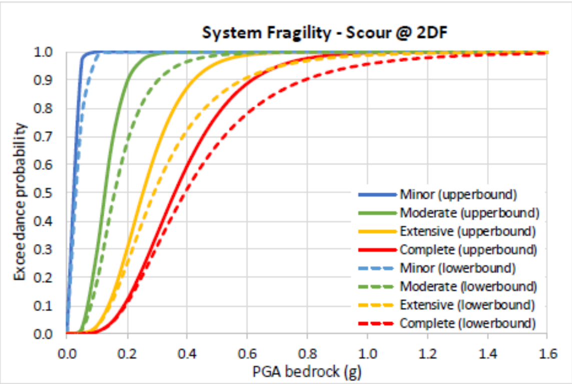
Pier



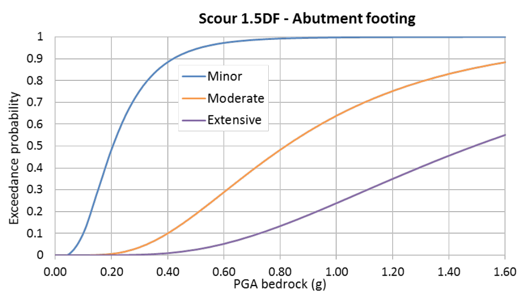
Backfill

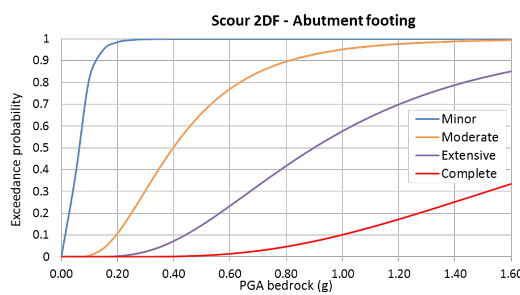






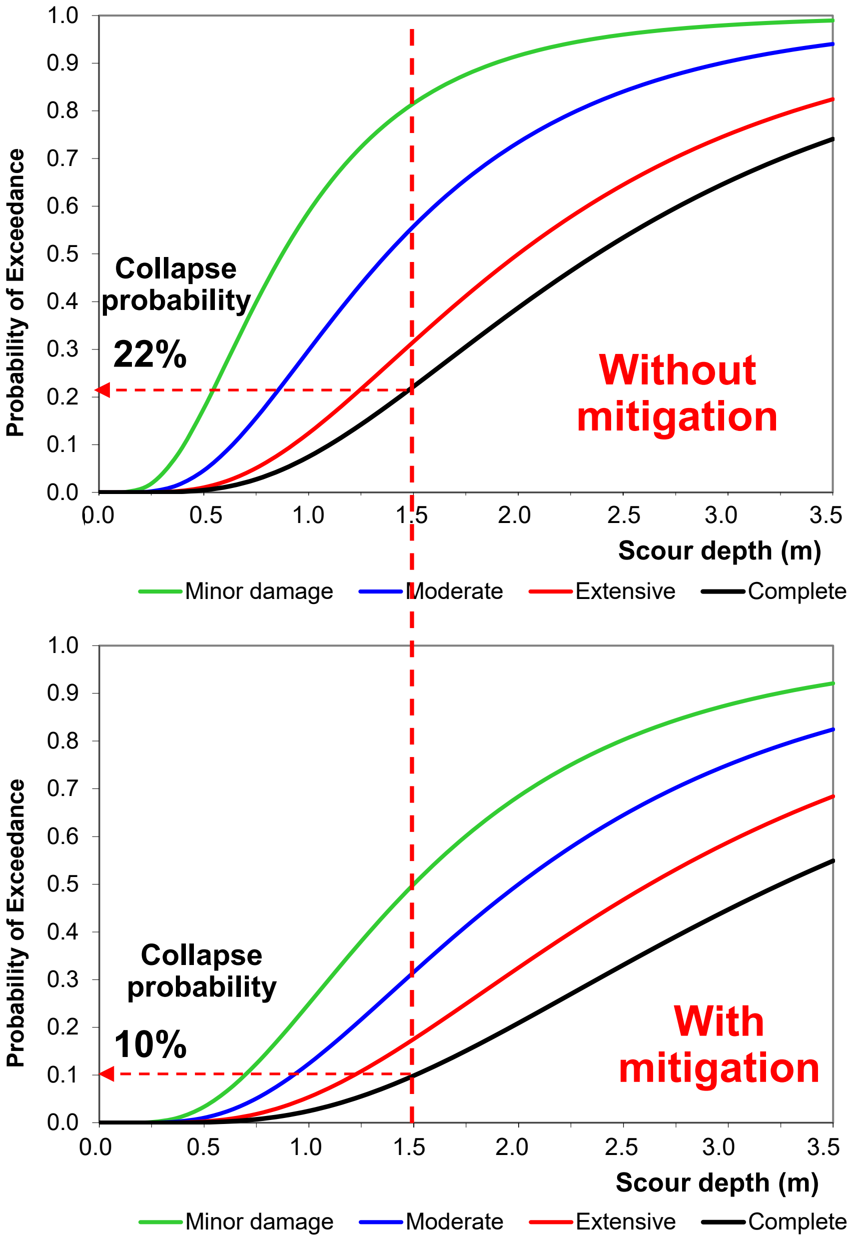
Abutment





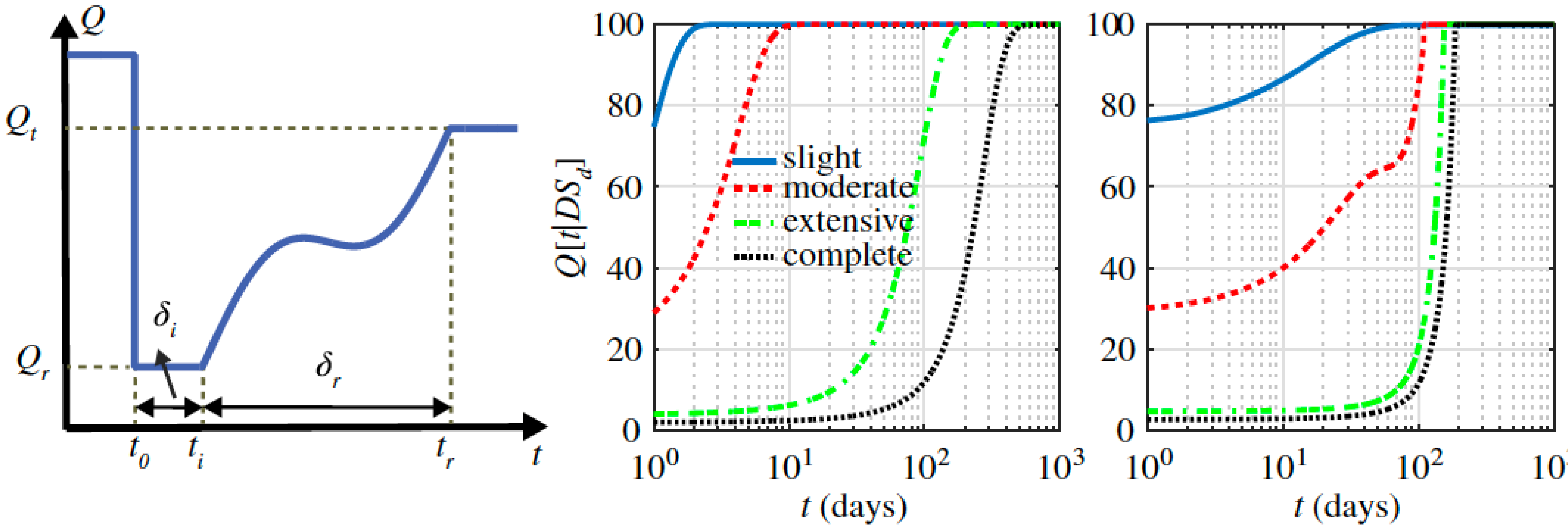
Effect of mitigation measures on the fragility of a bridge

Gabions for scour protection



note: these are hypothetical fragility curves

Restoration models



(a) (b) (c)

(a) illustration of functionality recovery process

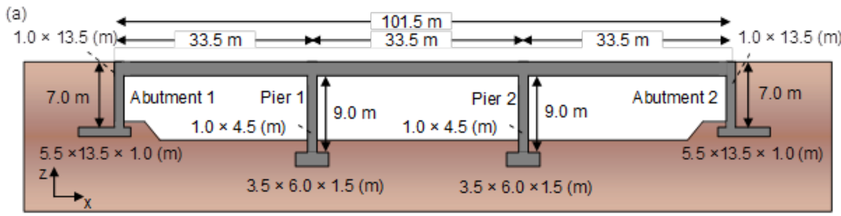
(b) Hazus (2011)

(c) Multi-parameter sinusoidal model (Bocchini et al.)

4R : Robustness, Redundancy, Resourcefulness, Rapidity

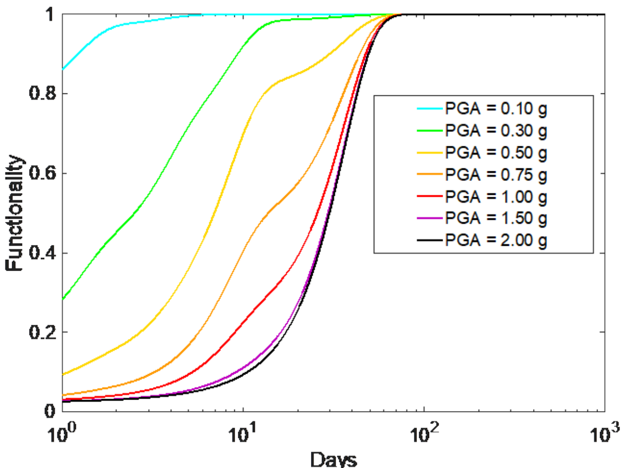
Resilience analysis

Improving resilience of a bridge with different restoration strategies

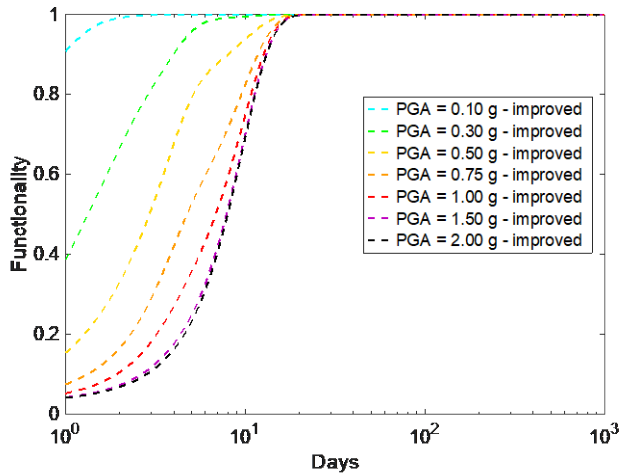


Resilience curves

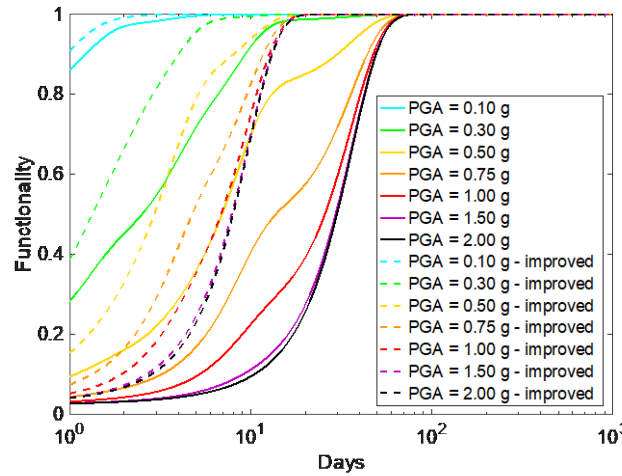
Original **restoration strategy**



Improved **restoration strategy**



Comparison



$$R = \frac{1}{t_h - t_o} \int_{t_o}^{t_h} Q(t)$$

$$R_{orig} < R_{impr}$$

Survey for bridge restoration after floods for generating resilience models

Contents:

1. Instructions,
2. Restoration tasks,
3. Quantification of the fragility and restoration of a 3-span pre-stressed concrete bridge,
4. Foundations,
5. Piers,
6. Abutments & wingwalls,
7. Bearings,
8. Deck,
9. Backfill & approach slab

Estimate for each damage state:

- **Idle or lag time** (e.g. emergency response, removal of standing water, inspection and condition assessment, site investigation, structural and foundation evaluation, design of measures, including organisational barriers)
- **% traffic capacity** (% of the normal bridge capacity) in 0, 24 hours, 3, 7, 30, 60, 90, 180, 270, 365 days
- **Restoration task(s)**
- **Cost ratio:** a ratio of the construction cost of the entire bridge

Survey for bridge restoration after floods for generating resilience models

code	restoration task	duration (days)	
		minimum	maximum
(1)	(2)	(3)	(4)
R0	no action is required	na	na
R1	armouring countermeasures and flow-altering		
R2	temporary support per pier		
R3	temporary support of one abutment		
R4	temporary support of one deck span /segment (midspan or support)		
R5	repair cracks and spalling with epoxy and/or concrete		
R6	re-alignment and/or leveling of pier		
R7	re-alignment of bearings		
R8	jacketing or local strengthening (pier or abutment or foundation)		
R9	jacketing or local strengthening (deck)		
R10	re-alignment of deck segment		
R11	erosion protection measures		
R12	rip-rap and/or gabions for filling of scour hole and scour protection		
R13	removal of debris		
R14	ground improvement per foundation		
R15	installation of deep foundation system		
R16	extension of foundation footing		
R17	reconstruction/replacement of the abutment and wingwalls		
R18	reconstruction/replacement of the pier		
R19	temporary support and replacement of the bearings		
R20	replacement of the backfill and approach slab and mudjacking		
R21	replacement of expansion joint		
R22	demolish/replacement of a deck span/segment		
R23	demolish/replacement of the bridge		
R24	please add customised task		
R25	please add customised task		
R26	please add customised task		
R27	please add customised task		

Restoration times for different restoration tasks

Survey for bridge restoration after floods

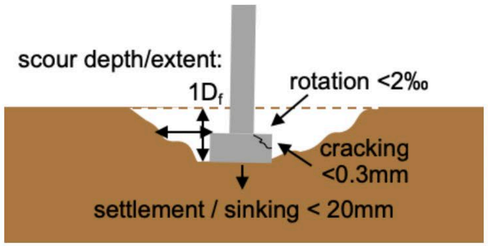
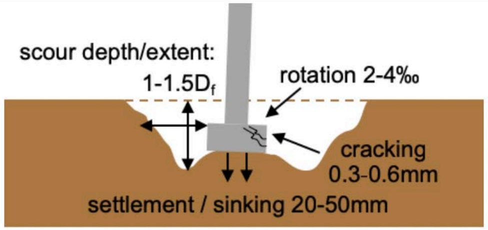
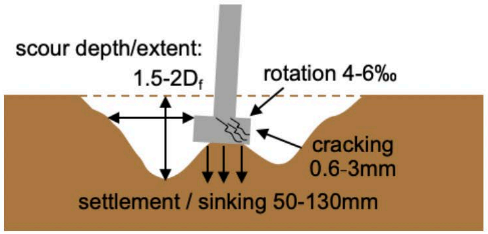
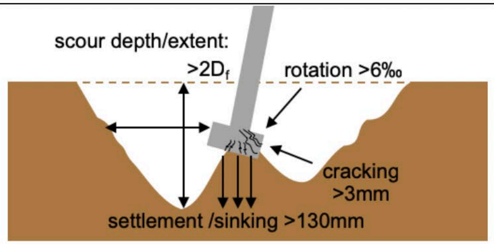
Restoration of hydraulic induced damage to spread foundations

Damage level *(see Table 4 for description)*	**Idle time (before any restoration works)**		**Restoration time in days (after the initiation of the restoration works)**										**Restoration tasks & prioritisation** *(see Table 2)*	**Cost ratio** *(% of replacement cost of the bridge)*
	min	**max**	**0**	**1**	**3**	**7**	**30**	**60**	**90**	**180**	**270**	**365**		
			% traffic capacity of the bridge after damage											
(1)	(2)	(3)	(4)										(5)	(6)
Minor														
Moderate														
Extensive														
Complete														

Comments:

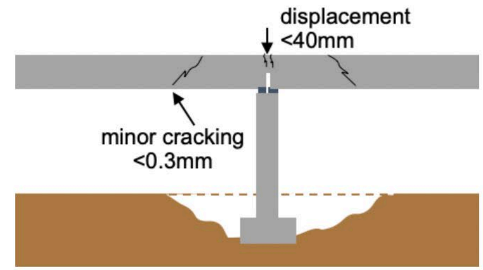
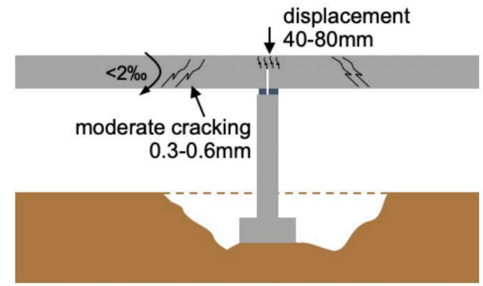
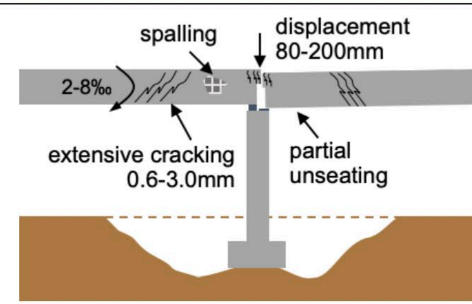
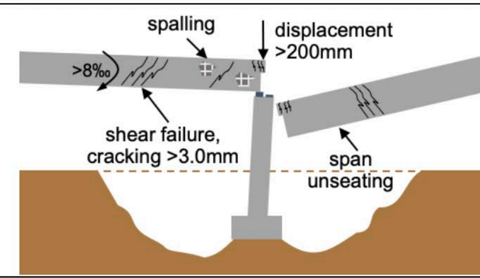
Survey for bridge restoration after floods

Description of damage levels for hydraulic induced damage to spread foundations

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

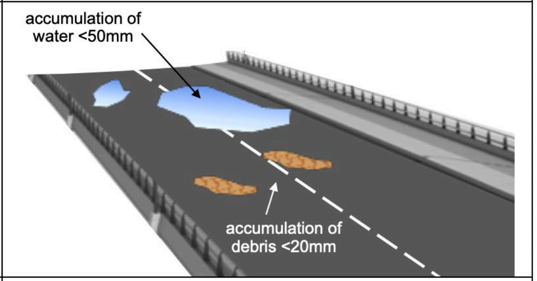
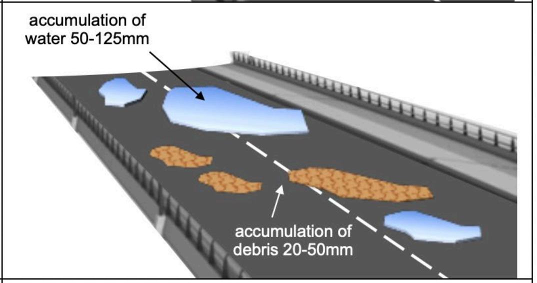
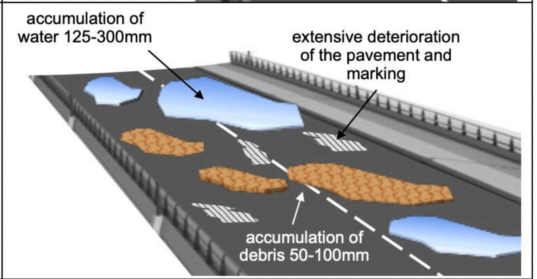
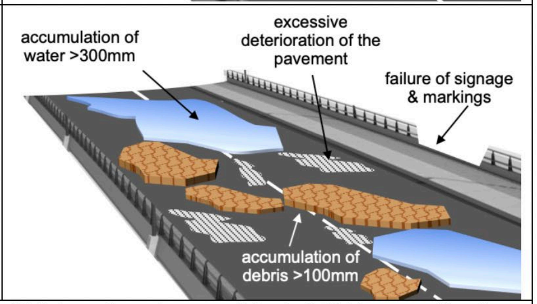
Survey for bridge restoration after floods

Description of damage levels for hydraulic induced damage to simply-supported deck

Damage level	Description	Sketch
Minor	- Minor spalling and cracking of the deck, cracking width: <0.3mm - Vertical and/or horizontal deflections/displacements of the deck: <40mm	
Moderate	- 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‰	
Extensive	- 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	
Complete	- 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	

Survey for bridge restoration after floods

Description of functionality loss levels for hydraulic induced disruptions to bridge deck

Functionality loss level	Description	Sketch
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)	
Excessive	- 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

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