ERMABI Workshop – Exploiting the Resilience of Masonry Arch Bridge Infrastructure

University of Strathclyde Glasgow

Risk assessment and monitoring of masonry bridges exposed to scour

Enrico Tubaldi – Reader in Structural Engineering
University of Strathclyde, Glasgow, UK

06 Sept 2023

enrico.tubaldi@strath.ac.uk

Outline

- Brief introduction to bridge scour
- Effects of scour on masonry arch bridges
- Monitoring approaches
- Monitoring system

Outline

- **Brief introduction to bridge scour**
- Effects of scour on masonry arch bridges
- Monitoring approaches
- Monitoring system

Bridge scour

- **Removal** of bed material around bridge foundations during floods.

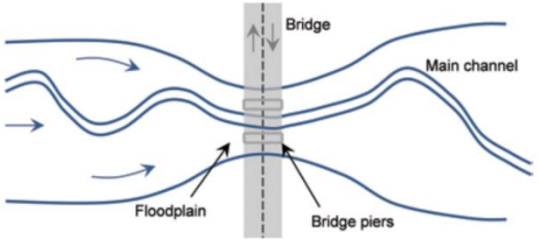
- Different types of bridge scour:

Aggradation/Degradation D_D

- Evolution of riverbed due to natural/human-induced causes

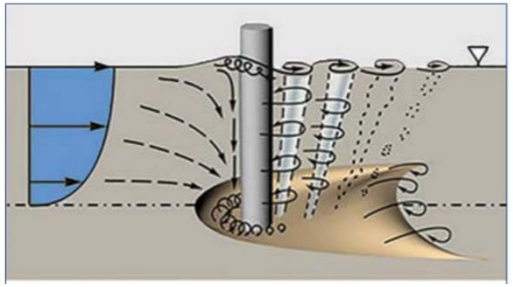
Constriction scour D_C

- River flow
- Width of channel/bridge
- River stage



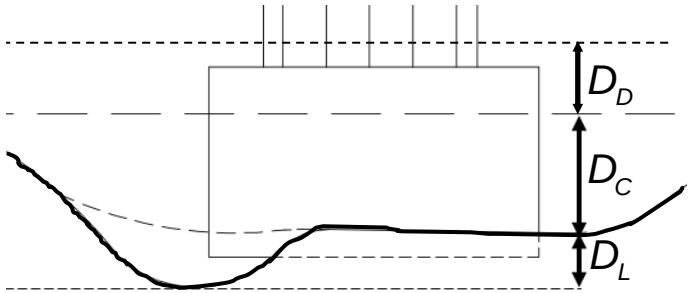
Local Scour D_L

- Pier geometry
- Angle of attack



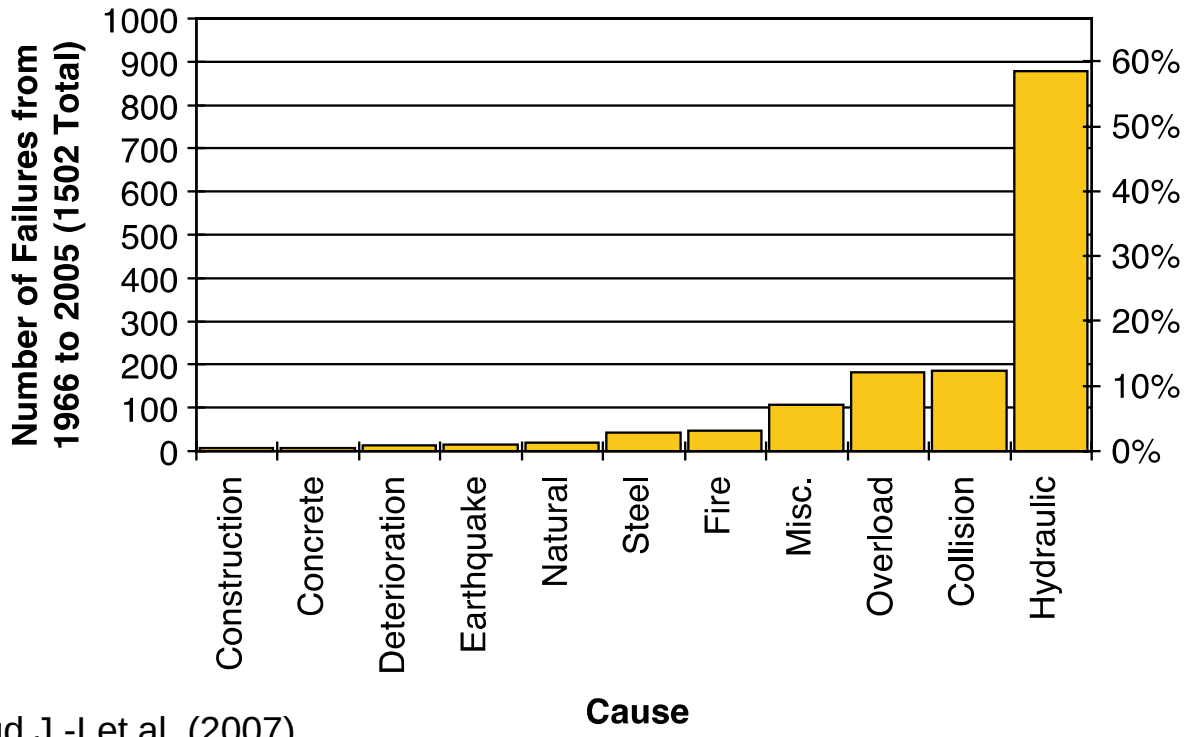
- **Total scour depth D_T**

$$D_T = D_D + D_C + D_L$$

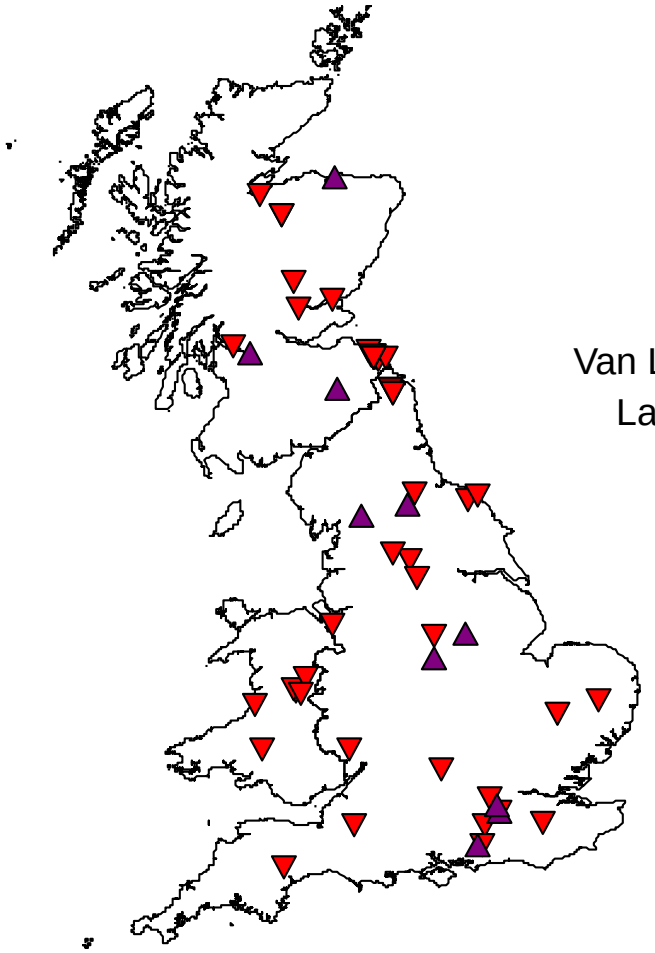


Bridge damage due to scour

- Flood-induced scour leading cause of bridge failure worldwide
- In the **USA** recorded **878 scour failures** in the period 1966-2005 (22/year on average)
- In the **UK** there were **138** railway bridge failures during 1846-2013
- Increasing trend of scour failure due to climate change



Briaud J.-Let al. (2007)



Van Leeuwen and Lamb (2014)

Geographical distribution of incidents

Bridge damage due to scour

Rubbianello Bridge, Italy
(50 minutes from hometown!)

Lamington Viaduct, Scotland
(50 minutes from home in Glasgow!)

- **Transport Scotland** responsible for **2029** bridges and culverts crossing waterways, **8%** need monitoring and scour protection measures, **£3.5m** of known scour repairs works to carry out
- **Network Rail** routinely inspects for scour **1750** bridge in Scotland, **58** considered at high risk, projected spend of **£27m** on scour protective works from 2014-19 in the UK

Research challenges

- Evaluating the **vulnerability** and **risk** of bridges exposed to floods and scour
- Improving current procedures for **long-term bridge risk management** and **rapid response to floods**
- Developing innovative and **low-cost sensors and techniques** for monitoring scour-critical bridges
- Quantifying the benefits of **Structural Health Monitoring** in managing bridge scour risk

Research challenges

European Geosciences Union

Natural Hazards and Earth System Sciences

Invited perspectives: challenges and future directions in improving bridge flood resilience

Enrico Tubaldi[1], Christopher J. White[1], Edoardo Patelli[1], Stergios Mitoulis[2], Gustavo de Almeida[3], Jim Brown[4], Michael Cranston[5], Martin Hardman[6], Eftychia Koursari[7], Rob Lamb[8], Hazel McDonald[5], Richard Mathews[9], Richard Newell[10], Alonso Pizarro[11], Marta Roca[12], and Daniele Zonta[13]

[1]University of Strathclyde, UK
[2]University of Surrey, UK
[3]University of Southampton, UK
[4]Transport Scotland, UK
[5]Scottish Environment Protection Agency, UK
[6]Cumbria County Council, UK
[7]Amey, UK
[8]JBA Trust, UK and Lancaster University, UK
[9]Mott MacDonald, UK
[10]Network Rail, UK
[11]Universidad Diego Portales, Chile
[12]HR Wallingford, UK
[13]University of Trento, Italy

amey

JBA consulting

TRANSPORT SCOTLAND
CÒMHDHAIL ALBA

NetworkRail

HR Wallingford

Cumbria County Council

SEPA
Scottish Environment Protection Agency

MOTT MACDONALD

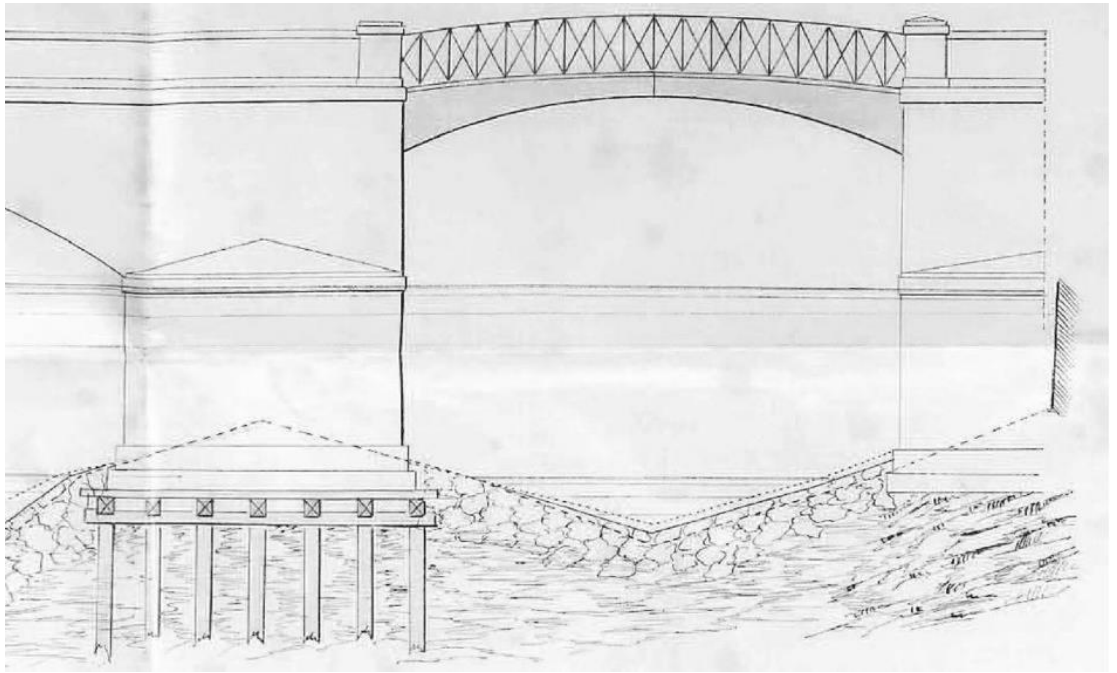
https://nhess.copernicus.org/preprints/nhess-2021-293/

Outline

- Brief introduction to bridge scour
- **Effects of scour on masonry arch bridges**
- Monitoring approaches
- Monitoring system

Vulnerability of masonry arch bridges to scour

- Built on shallow foundations and/or timber piles;
- Rigid structures that cannot accommodate settlements;
- Aged structures (>100 years).



(Malena et al. 2021)

Notable bridge failures

Brougham Old Bridge

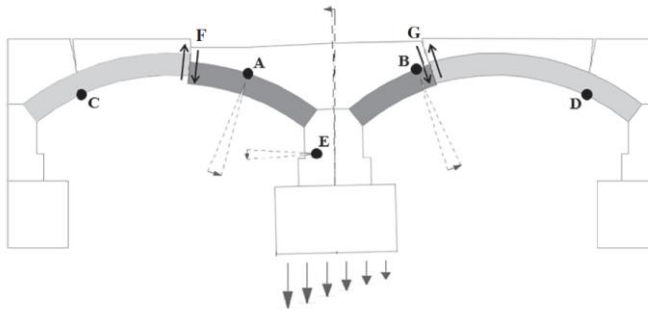
Ballynameen Bridge

Tadcaster Bridge

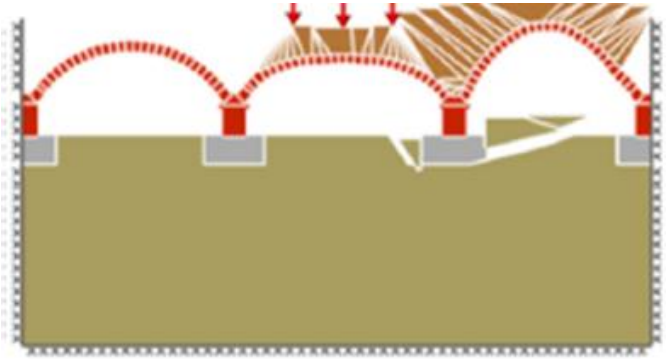
Feltham Bridge

Typical collapse mechanisms

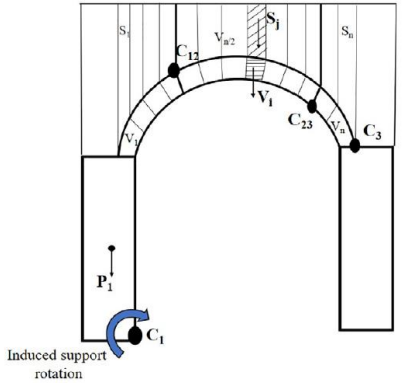
2d mechanisms



(Zampieri et al. 2017)

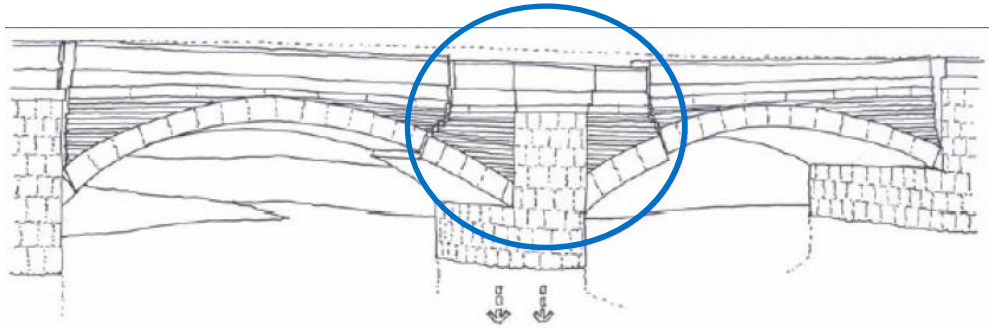


(Cabanzo et al. 2022)

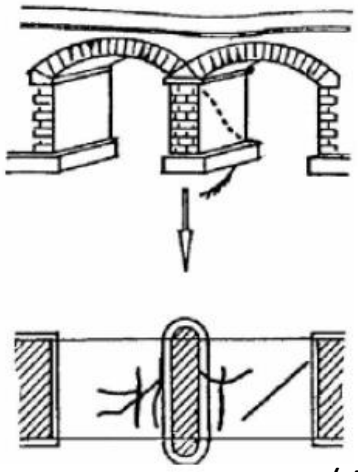


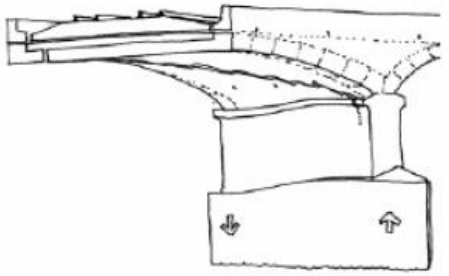
(George and Menon. 2021)

3d mechanisms



(Ozaeta and Martín-Caro 2006)

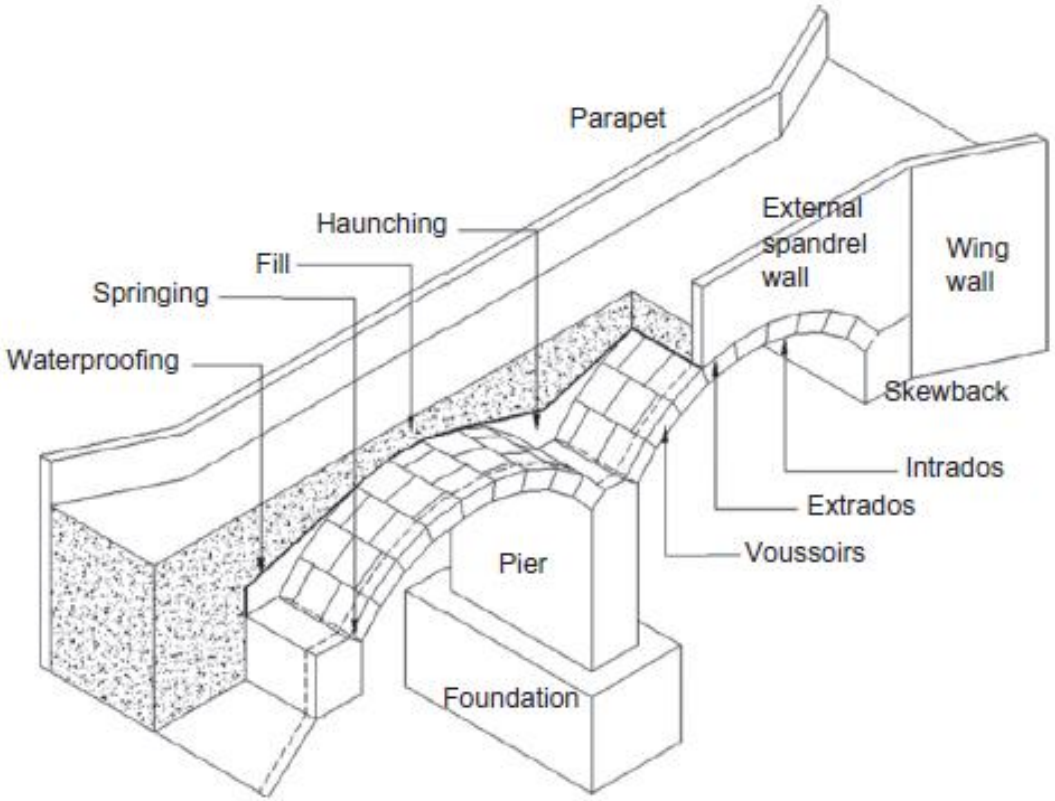




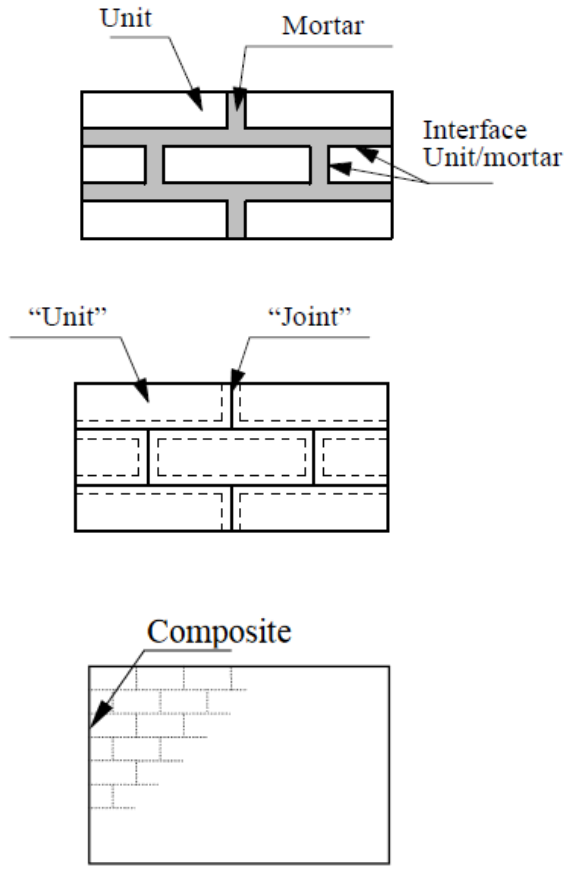
(Mathur et al. 2006)

12

Modelling of masonry arch bridges



- Alternative approaches:
  - Micro-scale models
  - Meso-scale models
  - Macro-models
  - Discrete-elements



Lourenco (1996)

Single ring

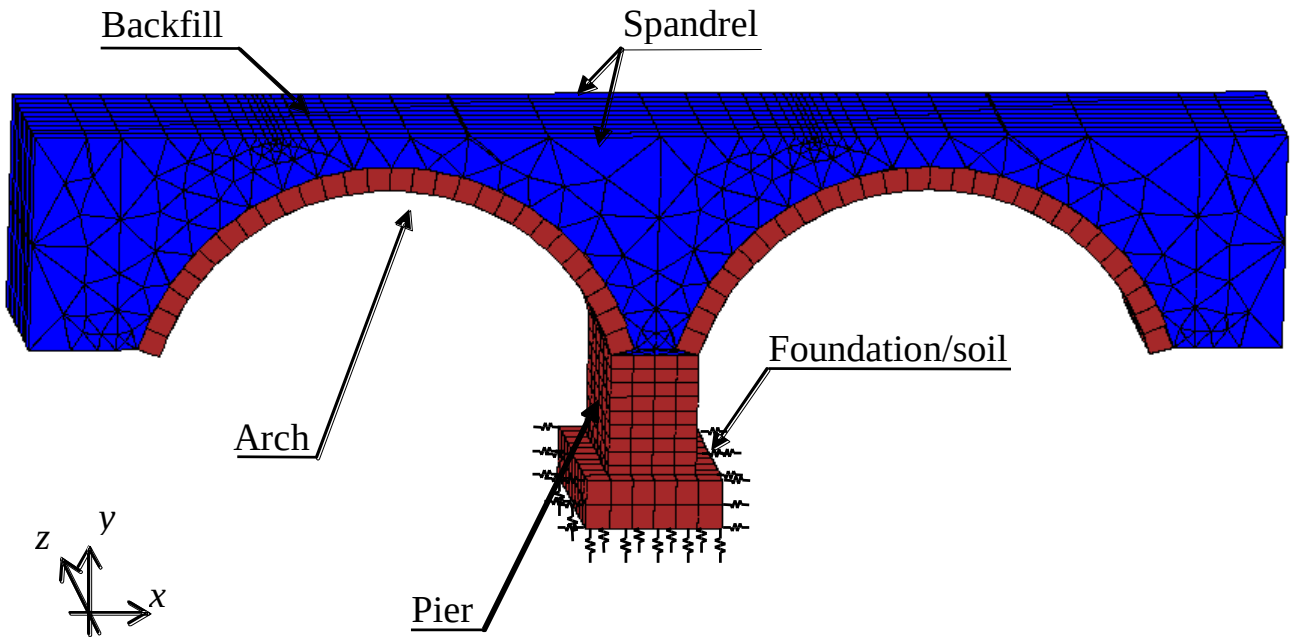
Multi-ring

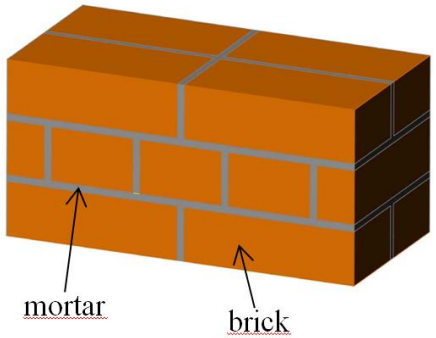
Multi-ring with headers

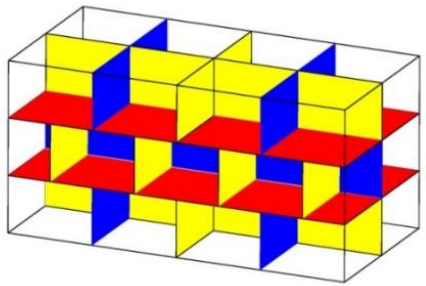
Analysis of Copley bridge

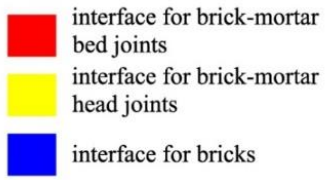
- Listed bridge in Yorkshire collapsed during Boxing Day flood in 2015.
- Three-dimensional collapse mechanism involving all the bridge components.

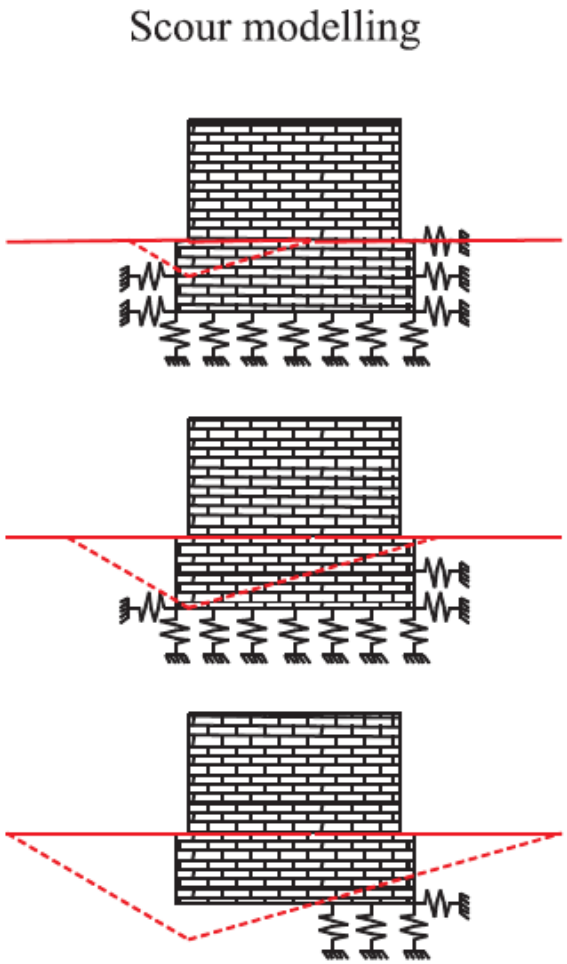
Analysis of Copley bridge



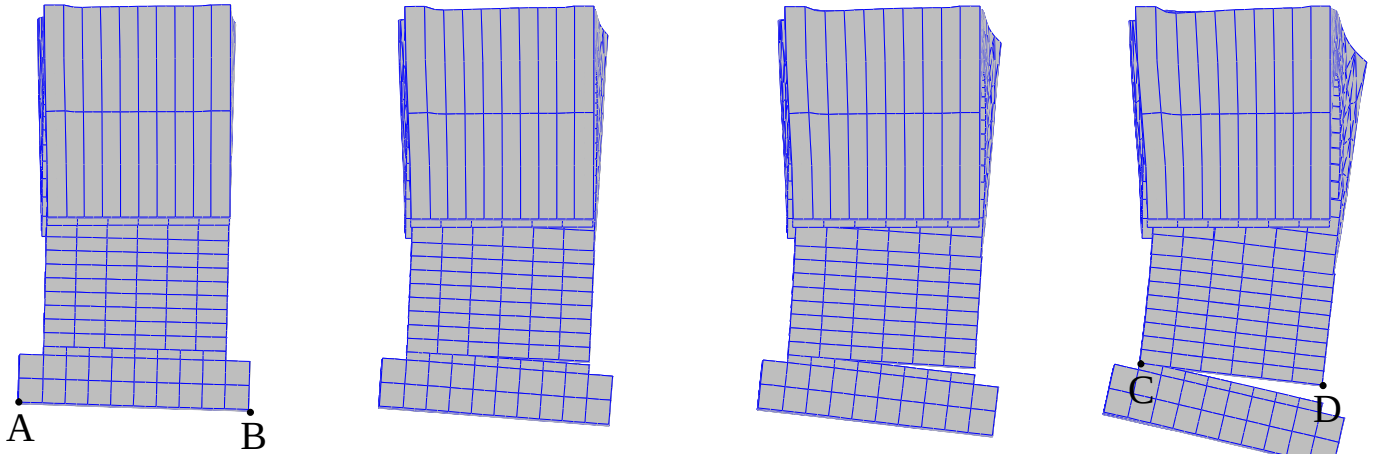




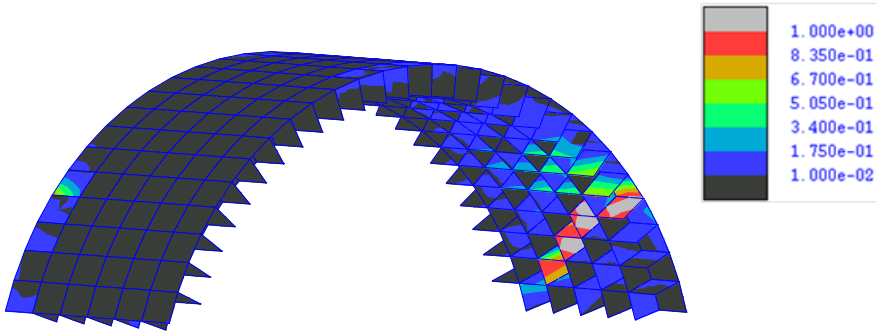


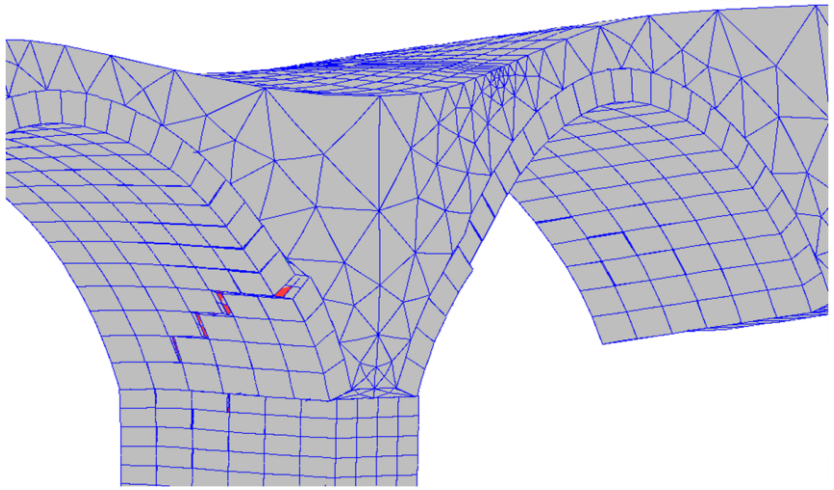


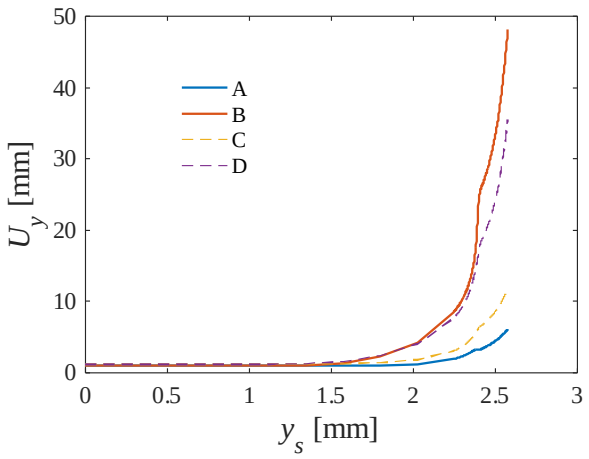
Analysis of Copley bridge

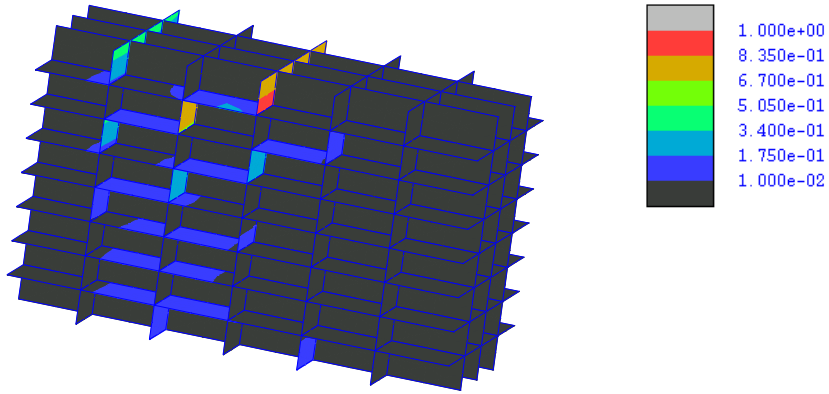


$y_s = 2.3$m $y_s = 2.4$m $y_s = 2.49$m $y_s = 2.6$m



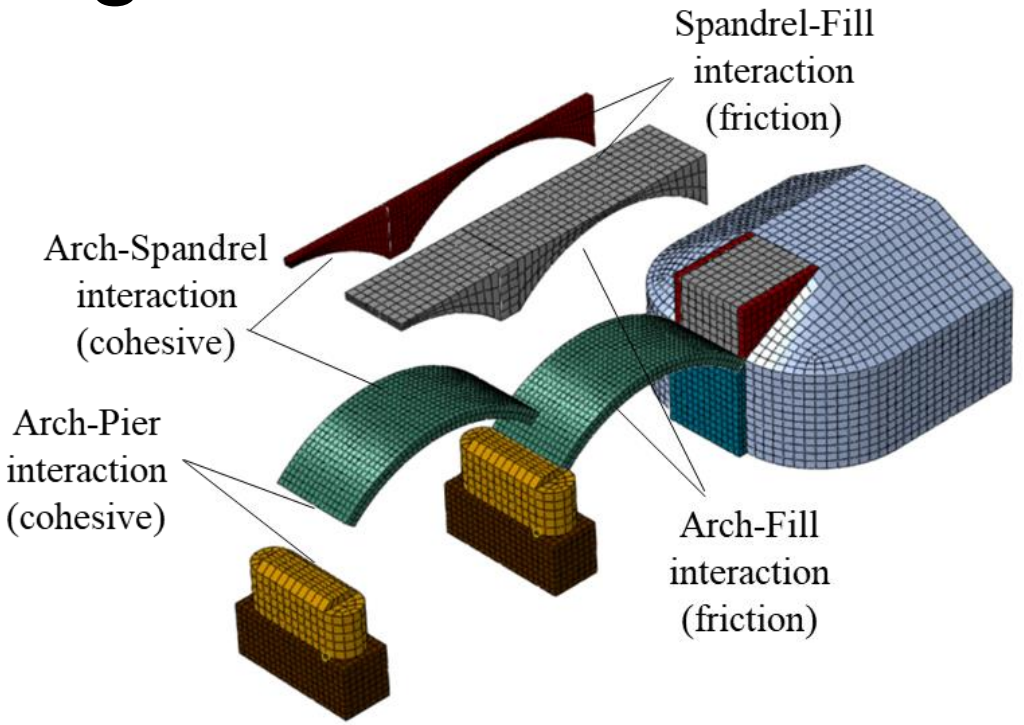






Analysis of Rubbianello bridge

Collapsed Rubbianello bridge, Italy

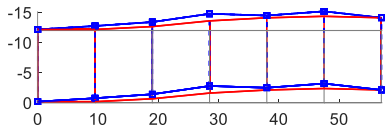


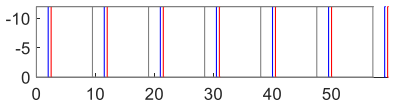
- Ambient vibrations measured with a set of accelerometers on the remaining bridge portion.

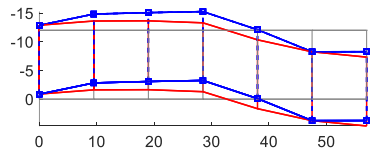
- Masonry material properties based on in-situ flat-jack tests

- Nonlinear 3d model developed in Abaqus

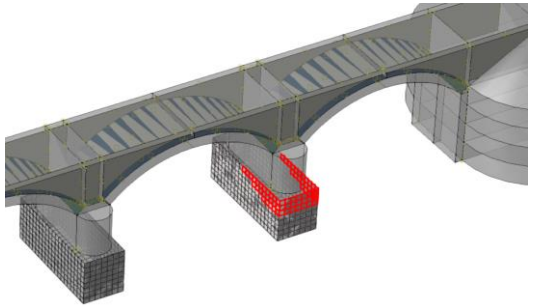
Mode [-]	Frequency [Hz]		Error [%]
	FEM	OMA	
1 (transversal)	6.16	5.90	-4.41
2 (longitudinal)	5.94	5.95	0.17
3 (transversal)	6.51	6.80	4.26



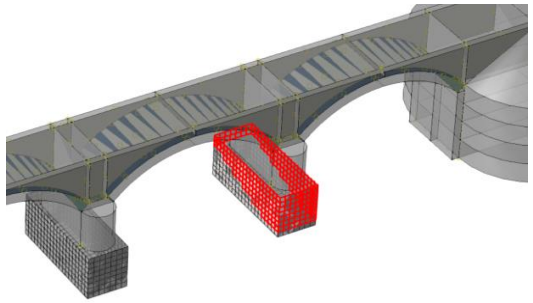




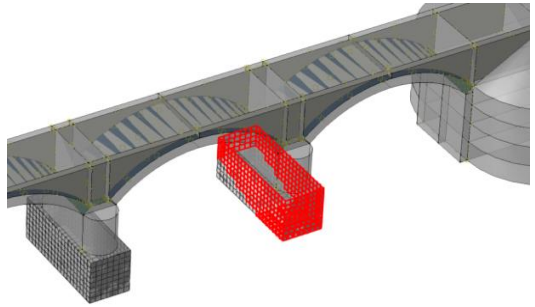
Analysis of Rubbianello bridge



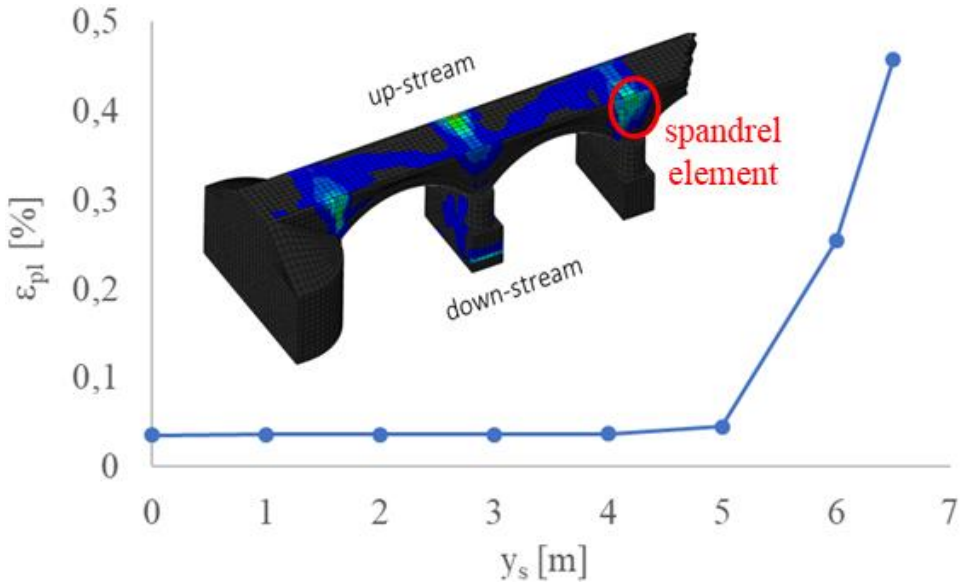
y_s = 2 m

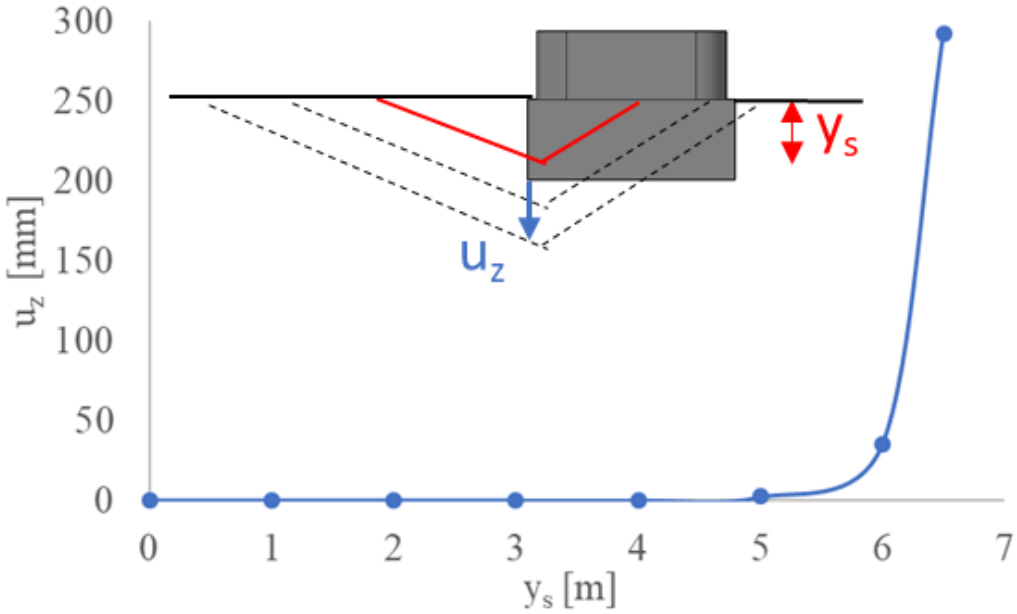


y_s = 4 m



y_s = 6 m

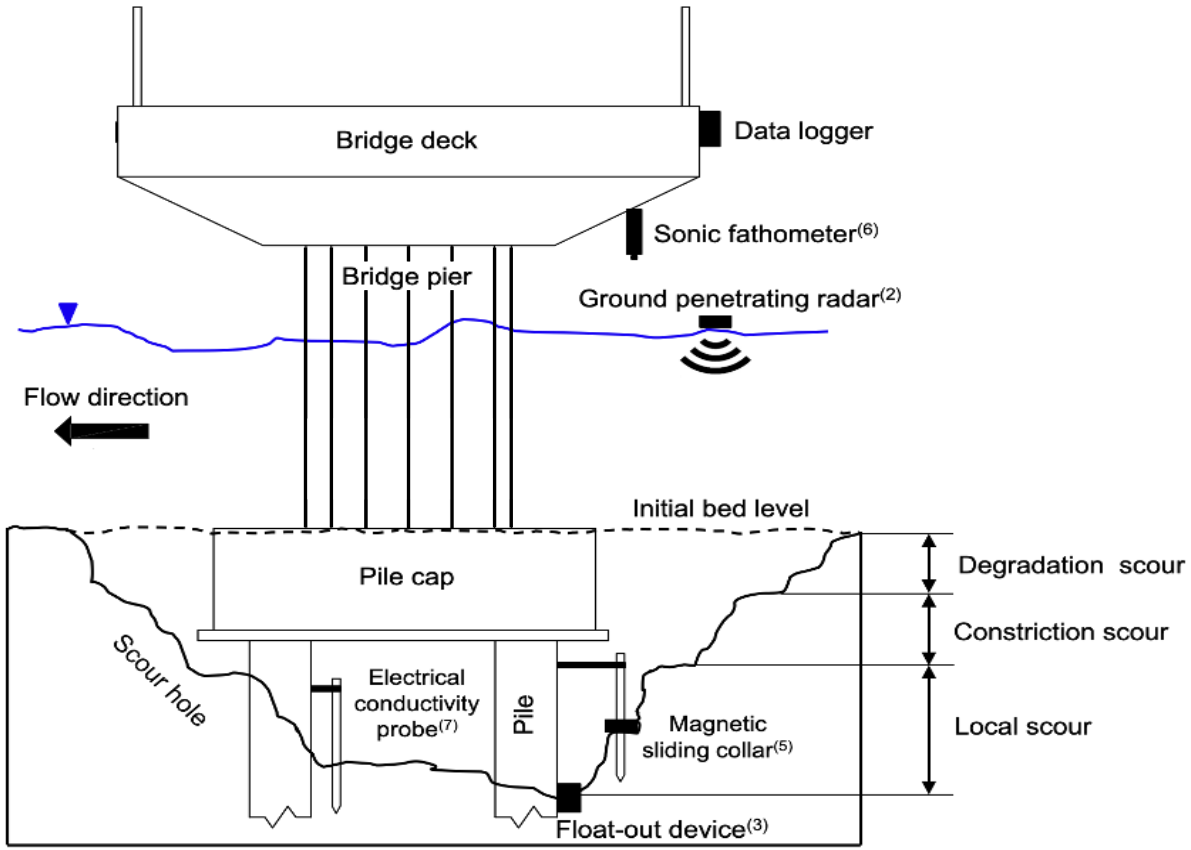




Outline

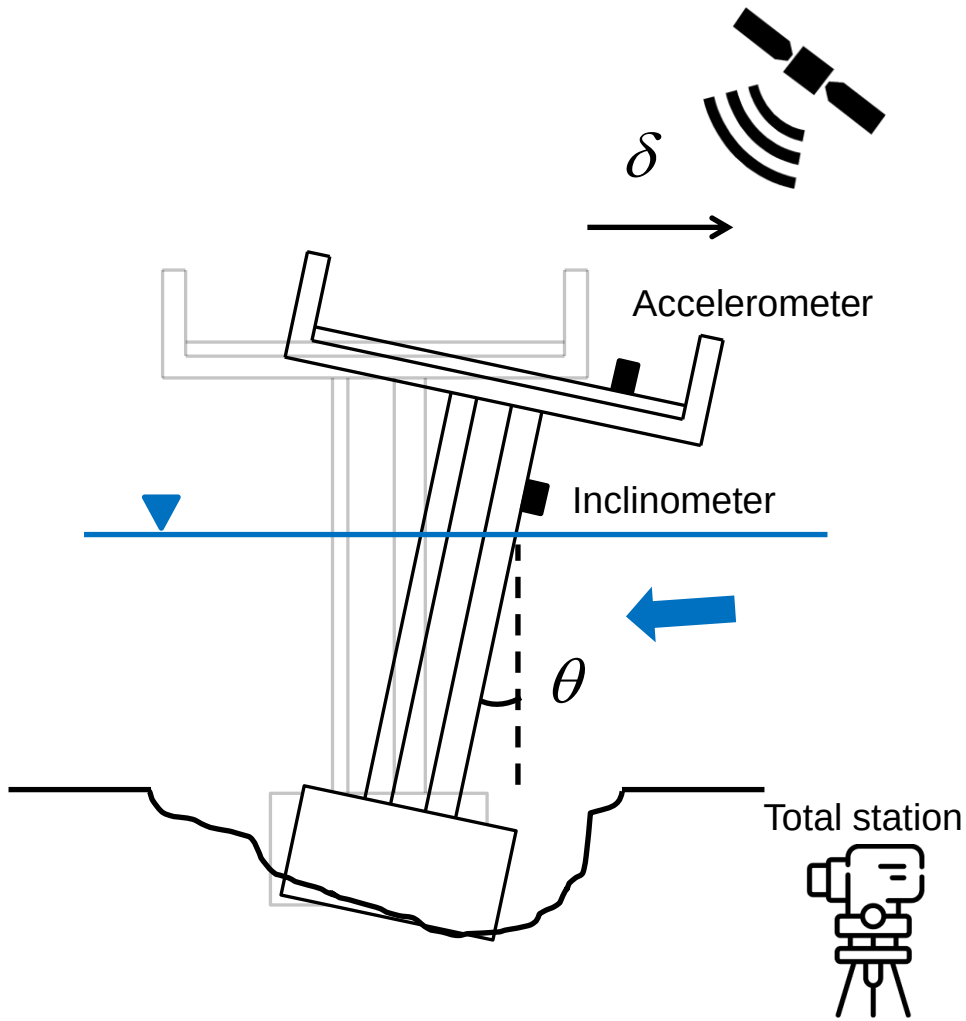
- Brief introduction to bridge scour
- Effects of scour on masonry arch bridges
- **Monitoring approaches**
- Monitoring system

MONITORING APPROACHES



Direct approaches

InSAR, GPS



Indirect approaches

SCOUR PROBES

- **Pilot scour sensing system** developed at the University of Strathclyde based on a commercial sensor (EnviroSCAN)
- **Sensing rod** equipped with **sensors** able to detect changes in the **dielectric permittivity** of the surrounding medium
- Allows to separate soil, water and deposition

Electromagnetic sensors

EnviroSCAN Probe

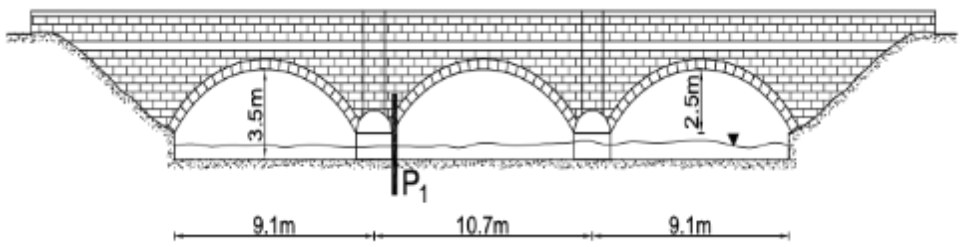
Access tube

Top cap allocating the DTU

Battery and 3G modem

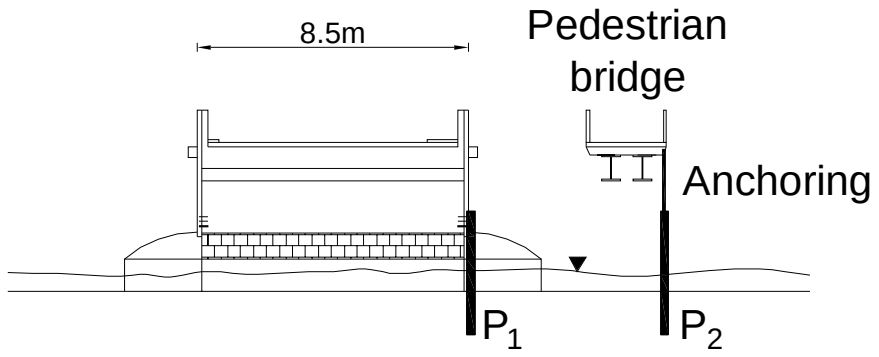
NERC PROJECT (NE/R009090/1)

SCOUR PROBES



Bridge in New Cumnock (A76 200)

- 3-span stone-masonry arch bridge
- Abutments and piers founded on spread footings on riverbed
- Classified at high scour risk

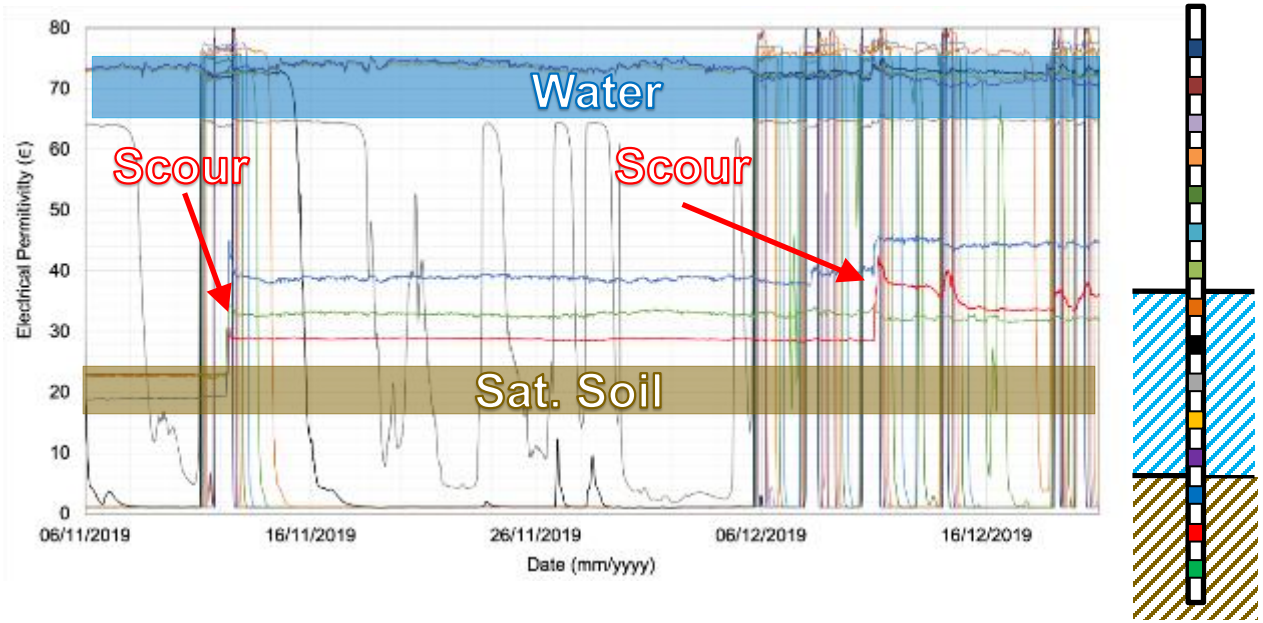


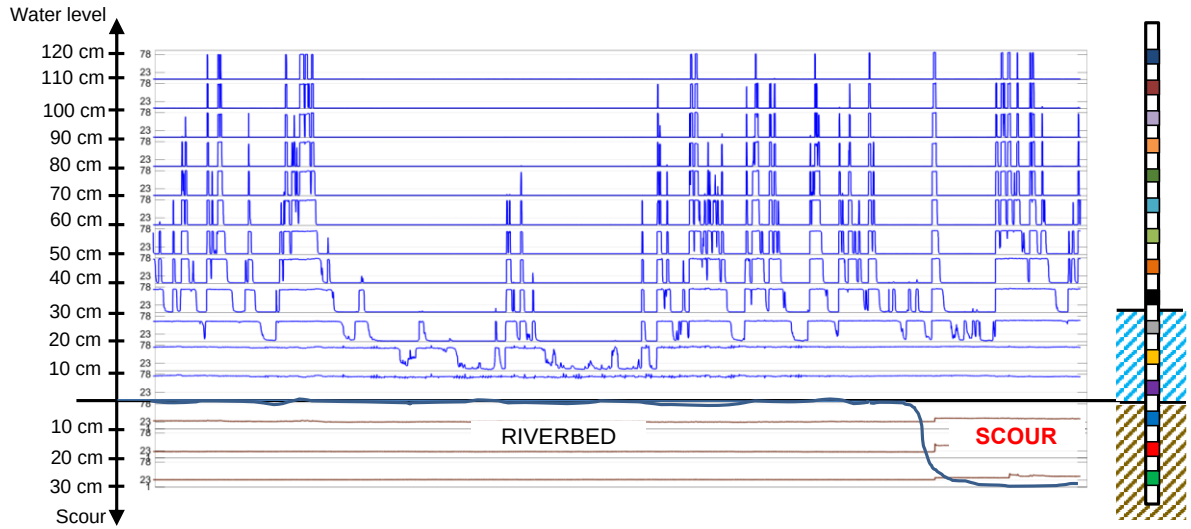
Scour probes

- 2 smart probes, P1 at the pier and P2 in the middle of riverbed
- 4-meters-long probes, 1.5 m sensing tip (16 sensors each)
- Water-sealed plastic tube
- Steel protecting tube anchored to the bridge (P1) and pedestrian bridge (P2)

SCOUR PROBES

- **Electrical permittivity** recorded during the monitoring period at **P2 location**
- Probe can record the **water level profile** and detected a **scour event**





SCOUR PROBES

Ae Old Bridge (1783)

- 2-span pedestrian bridge
- Pier founded on spread footings
- Experienced significant scour

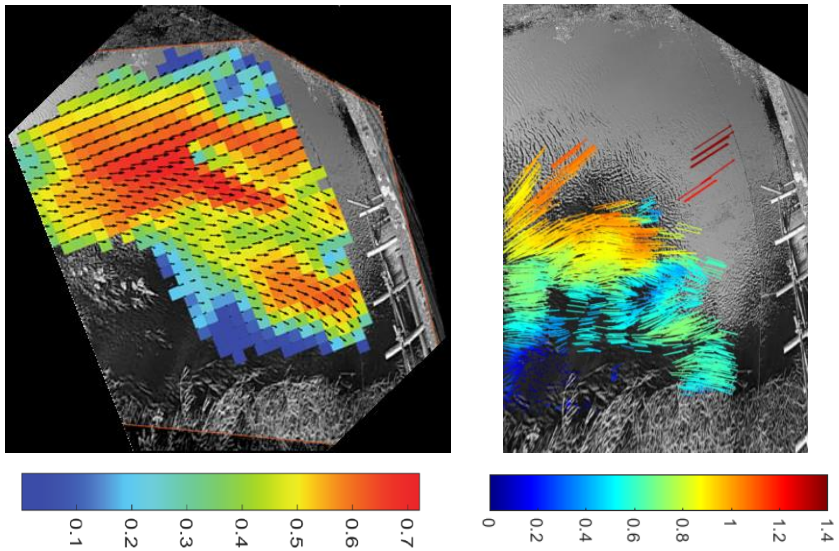
Auldgirth Old Bridge (1781)

- 3-span pedestrian bridge
- Piers founded on spread footings
- Experienced significant scour

Ae Old Bridge

REMOTE SENSORS

- Ultrasonic transducers for river level monitoring
- Particle image/tracking velocimetry analysis



- Radar velocity sensors (OTT SVR 100)
- Sonars/Fishfiders

Rivertrack IoT sensor

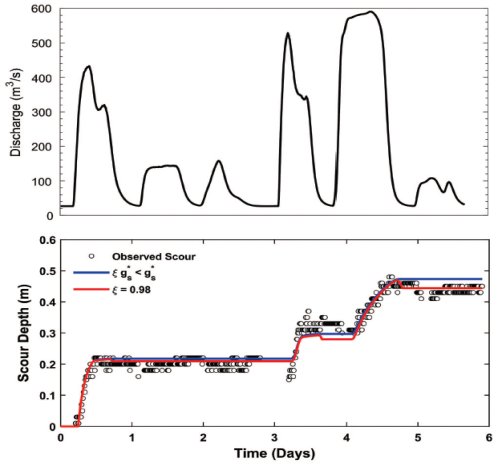
Wireless camera

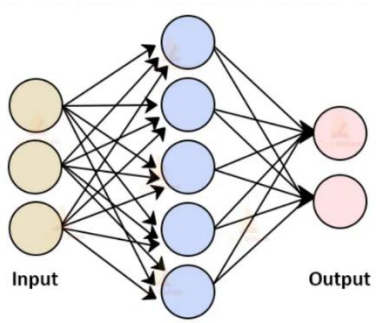
FROM FLOW PROPERTIES TO SCOUR

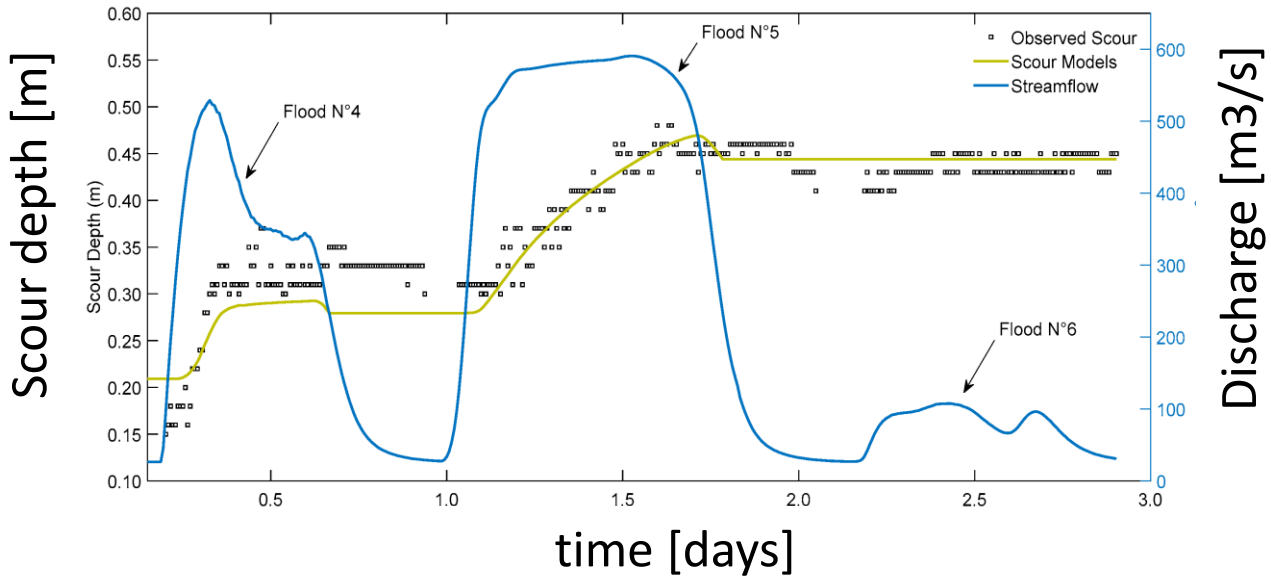
Monitored/forecasted river flow data (e.g. MetOffice, Rivertrack)

Real-time risk estimates/forecasts

Hydraulic models
AI/Machine learning-based models

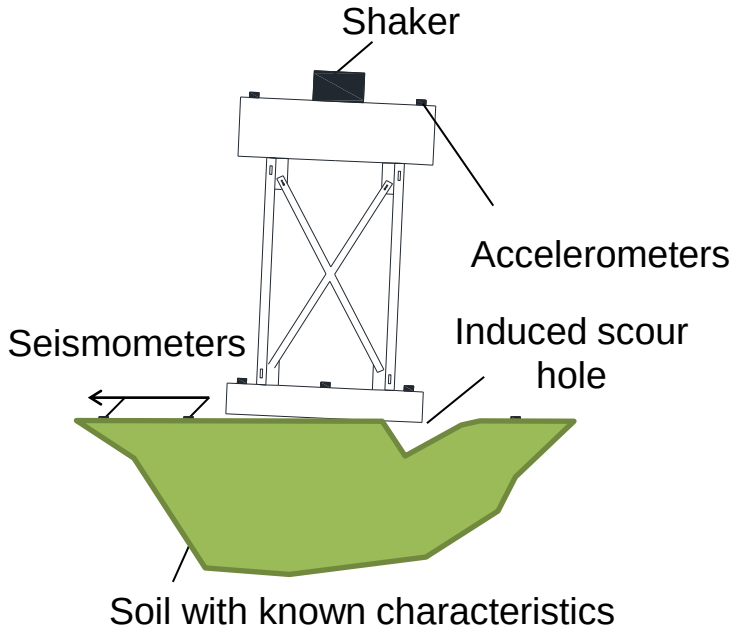


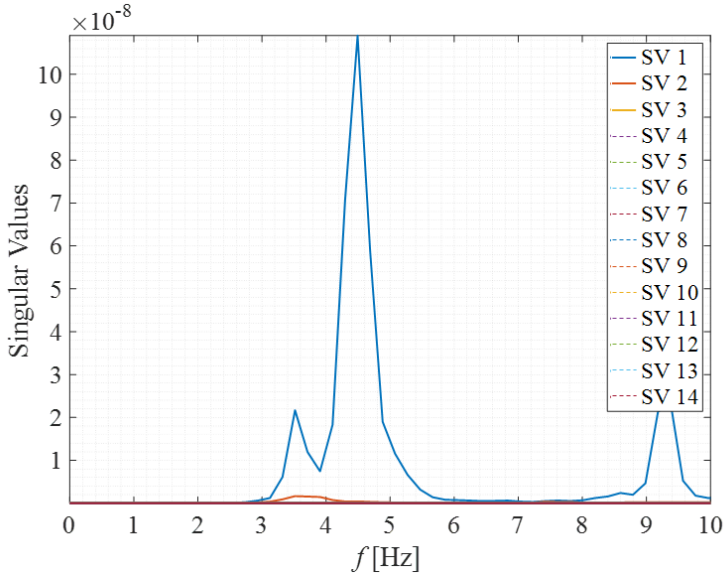




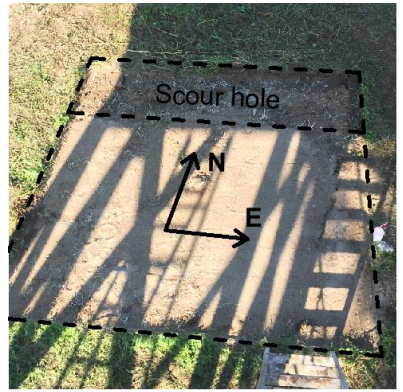
VIBRATION-BASED MONITORING

Dynamic identification and Monitoring of scoured BRIdgeS under earthquake hazard (DYMOBRIS)

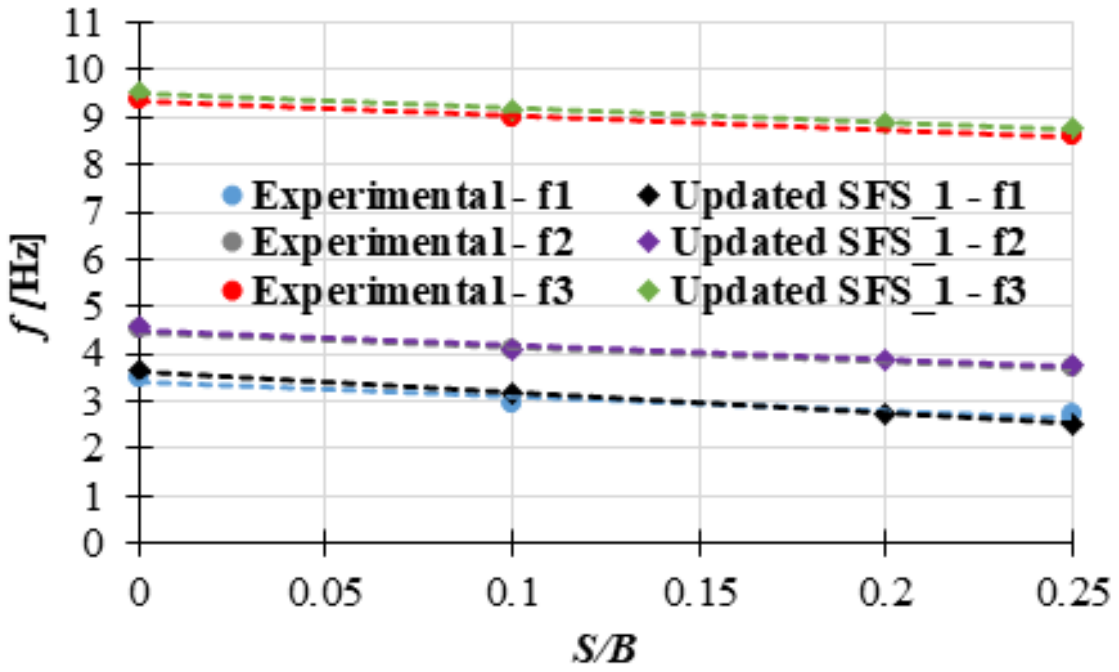


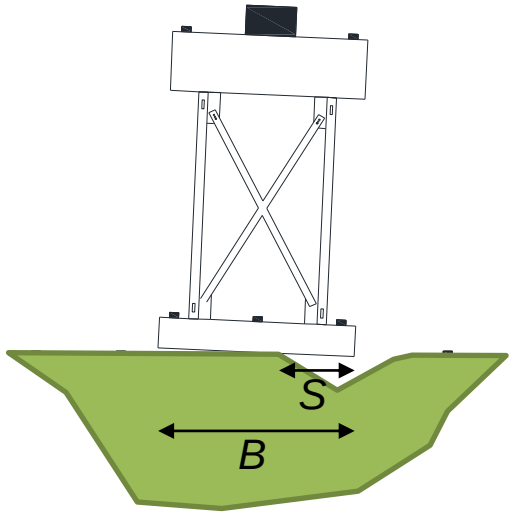


Host TA Facility: EUROSEISTEST and EUROPROTEAS



VIBRATION-BASED MONITORING



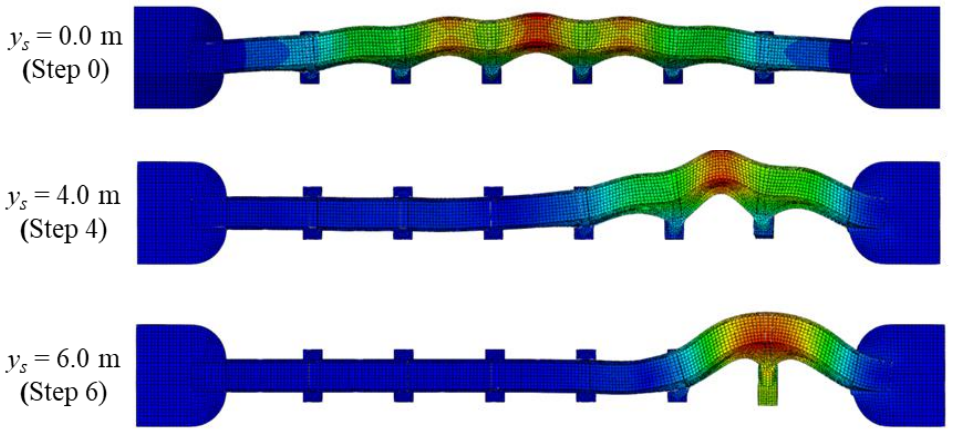


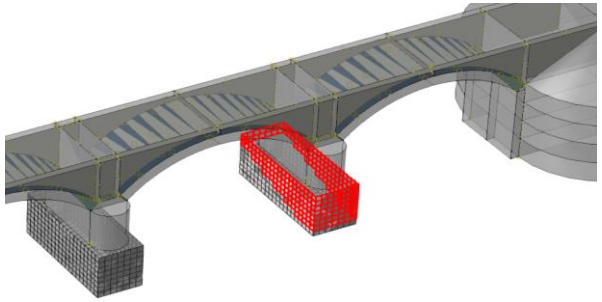
S/B = 0.23
f/f_0 = 0.8

- Linear decrease of the vibration frequencies for increasing levels of scour.
- Fundamental modes more affected than higher ones.
- For a scour width of 0.23B, fundamental frequency reduced only to 80% of value with no scour.
- Updated numerical model provides good estimates of the scour effects.

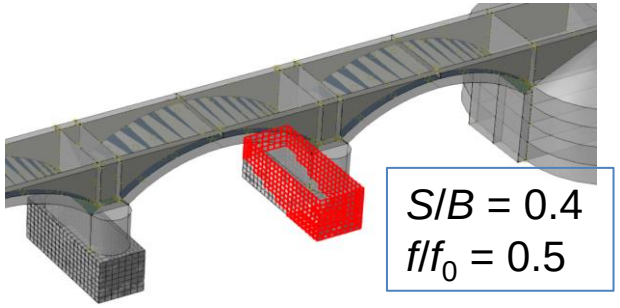
VIBRATION-BASED MONITORING

Rubbianello bridge, Italy

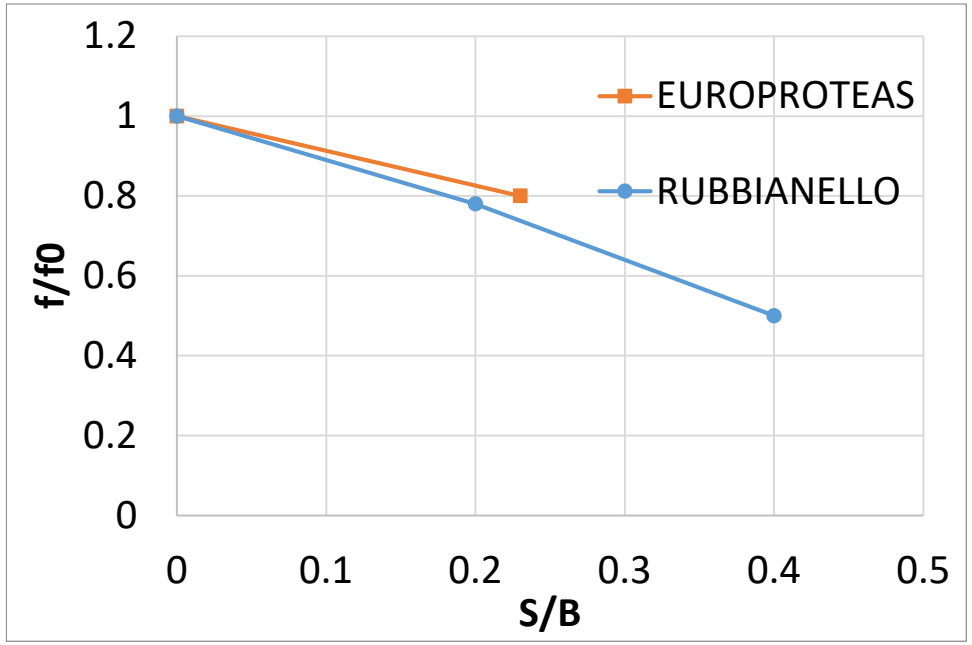




y_s = 4 m

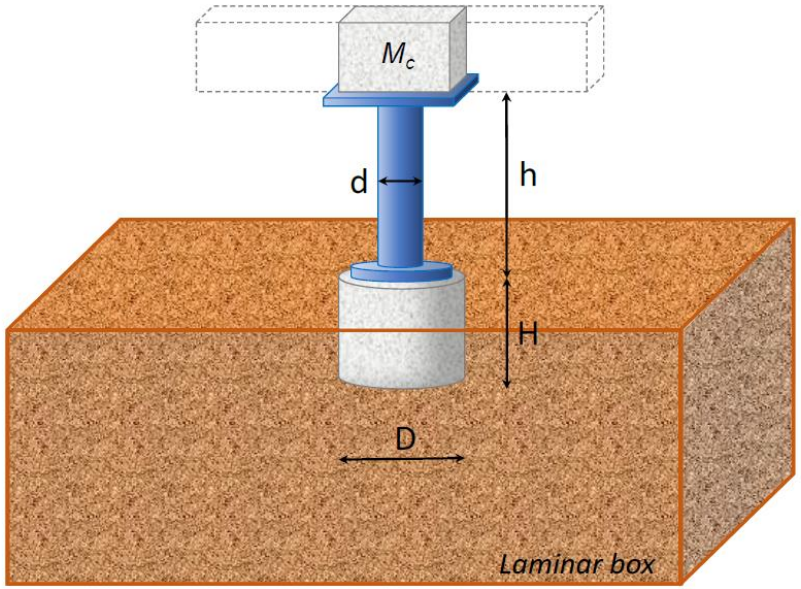


y_s = 6 m

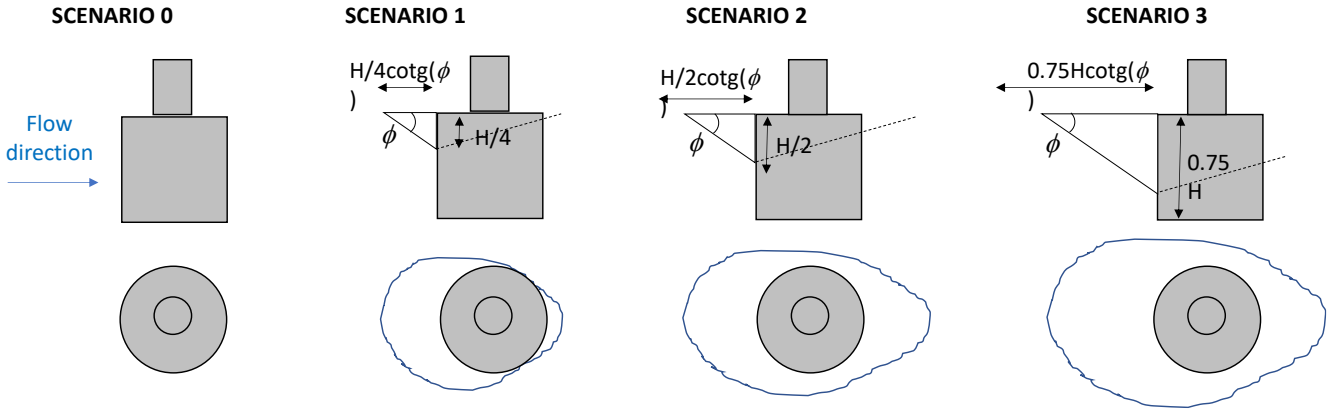


VIBRATION-BASED MONITORING

Structural Performance monitoring and evaluation of scoured bridges under dynamic actions (SCOUR & SHAKE)



UKCRIC Soil-Foundation-Structure Interaction (*SOFSI*) Laboratory



ERIES ENGINEERING RESEARCH INFRASTRUCTURES FOR EUROPEAN SYNERGIES

Outline

- Brief introduction to bridge scour
- Effects of scour on masonry arch bridges
- Monitoring approaches
- **Monitoring system**

SCOUR MONITORING SYSTEM

- Deploying scour sensors at every bridge at risk of scour is **economically unsustainable**

- This limitation can be overcome exploiting:
  - scour **monitoring** at **limited** and critical **locations**;
  - hydraulic and structural **models;**
  - a **probabilistic approach** to extend monitored data to unmonitored locations

Nith Bridge

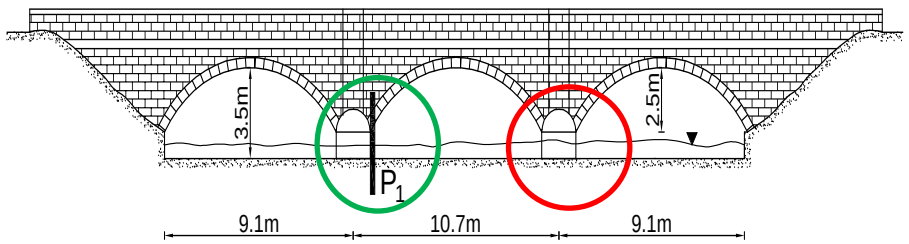
Guildhall Bridge

Dalscone Bridge

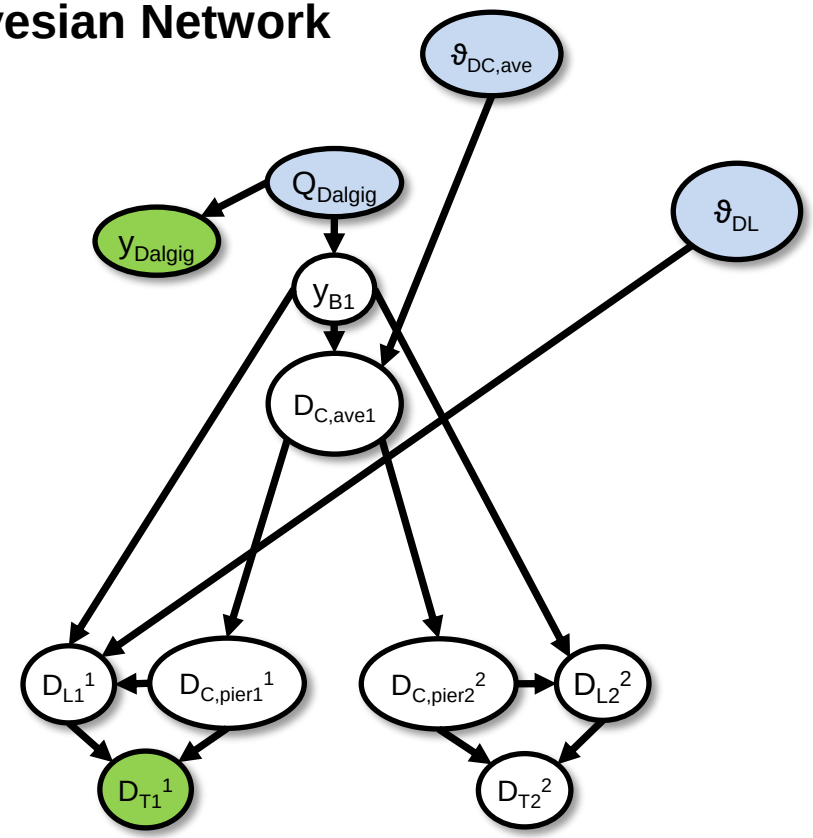
Scour monitoring of a pier in Bridge 1 → **Bayesian Network** → **Scour estimation at every location**

SCOUR MONITORING SYSTEM

A76 200 Bridge

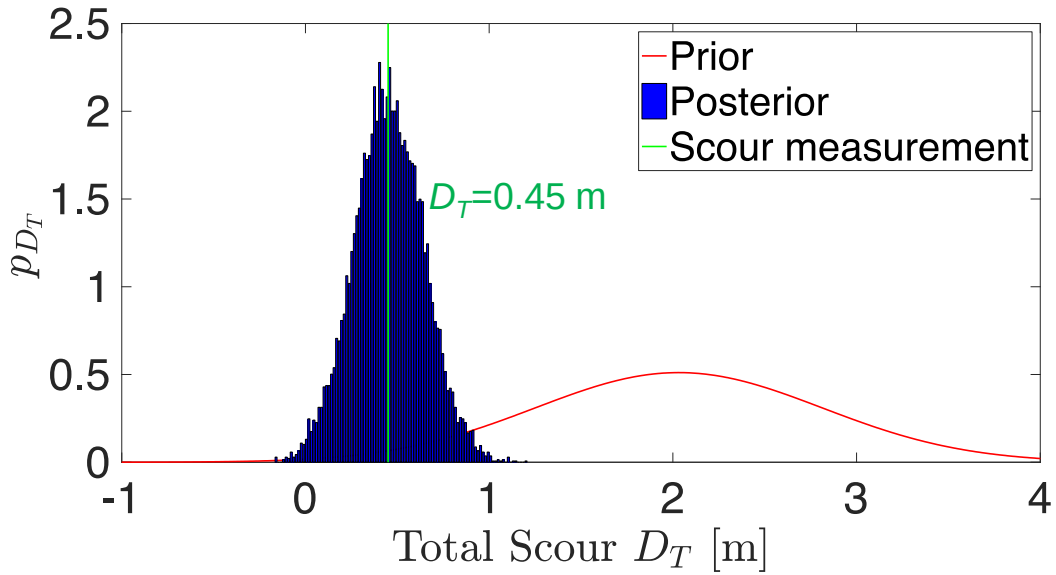


Bayesian Network



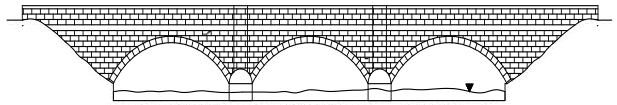
Observations from SHM systems

- Two scour probes installed at Pier 1 of Nith Bridge and on the bridge upstream
- Flow discharge monitored at a gauging station upstream of bridge

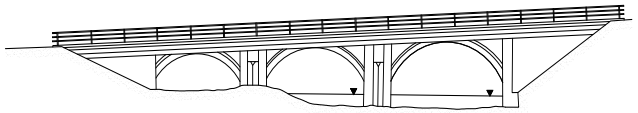


SCOUR MONITORING SYSTEM

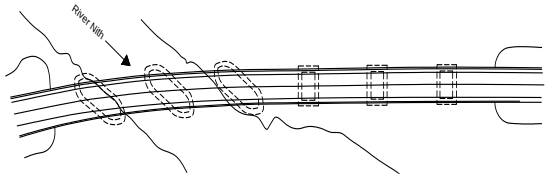
Nith Bridge

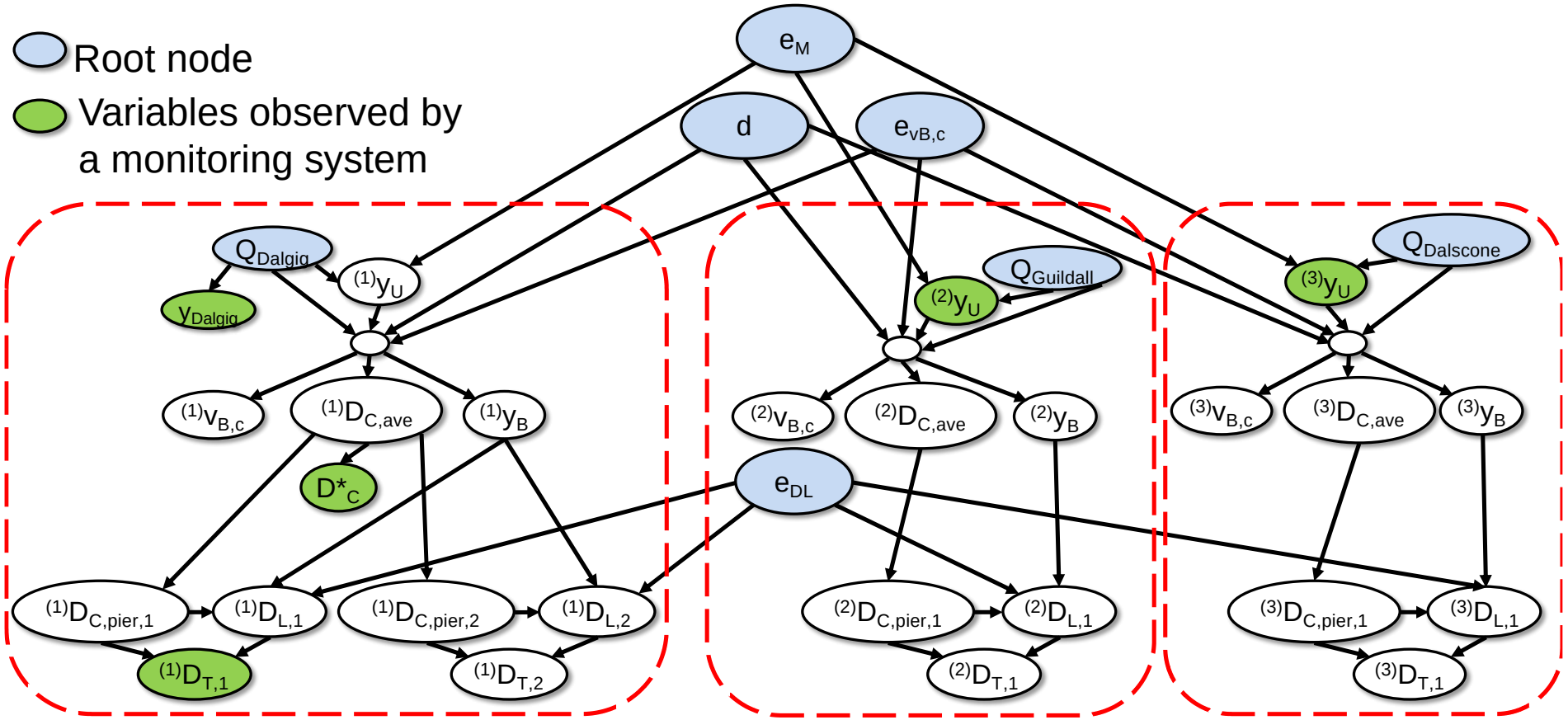


Guildhall Bridge



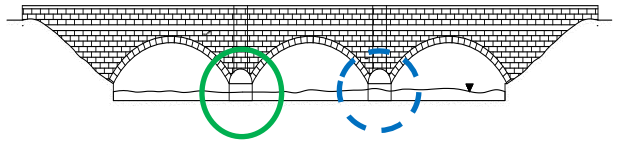
Dalscone Bridge

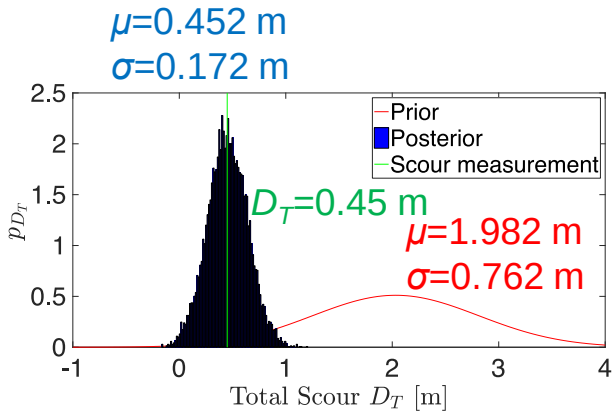




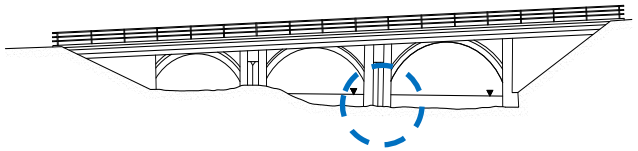
SCOUR MONITORING SYSTEM

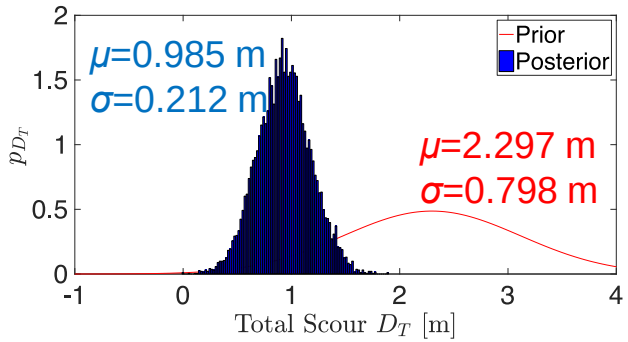
Nith Bridge



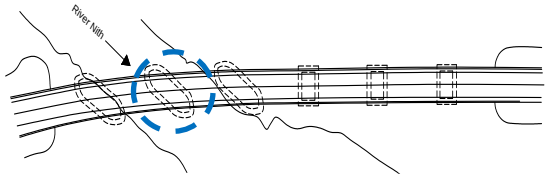


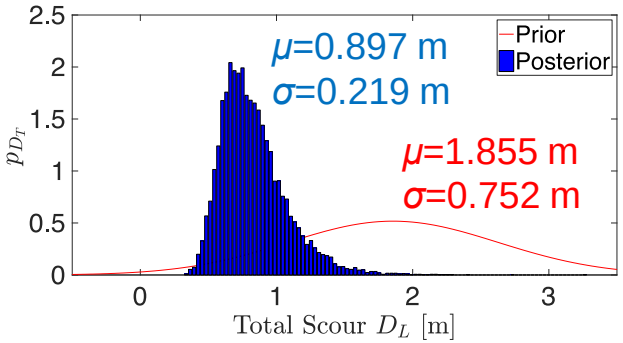
Guildhall Bridge





Dalscone Bridge

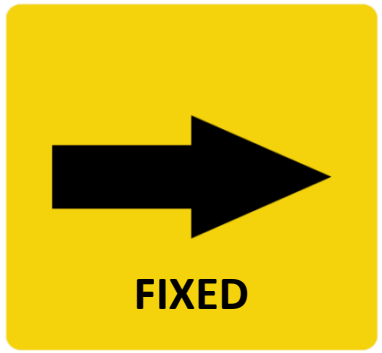




	Nith		Guildhall	Dalscone
	Pier 1	**Pier 2**	**Pier 1**	**Pier 1**
$\mu_{DT,p}$ [m]	1.979	1.982	2.297	1.855
$\sigma_{DT,p}$ [m]	0.739	0.762	0.798	0.752
μ_{DT} [m]	0.45	0.452	0.985	0.897
σ_{DT} [m]	-	0.172	0.212	0.219

The method estimates with good accuracy the scour also at the unmonitored bridges. There is an increase of the 70% in accuracy with respect to the prior results.

DECISION SUPPORT SYSTEM



CURRENT PRACTICE

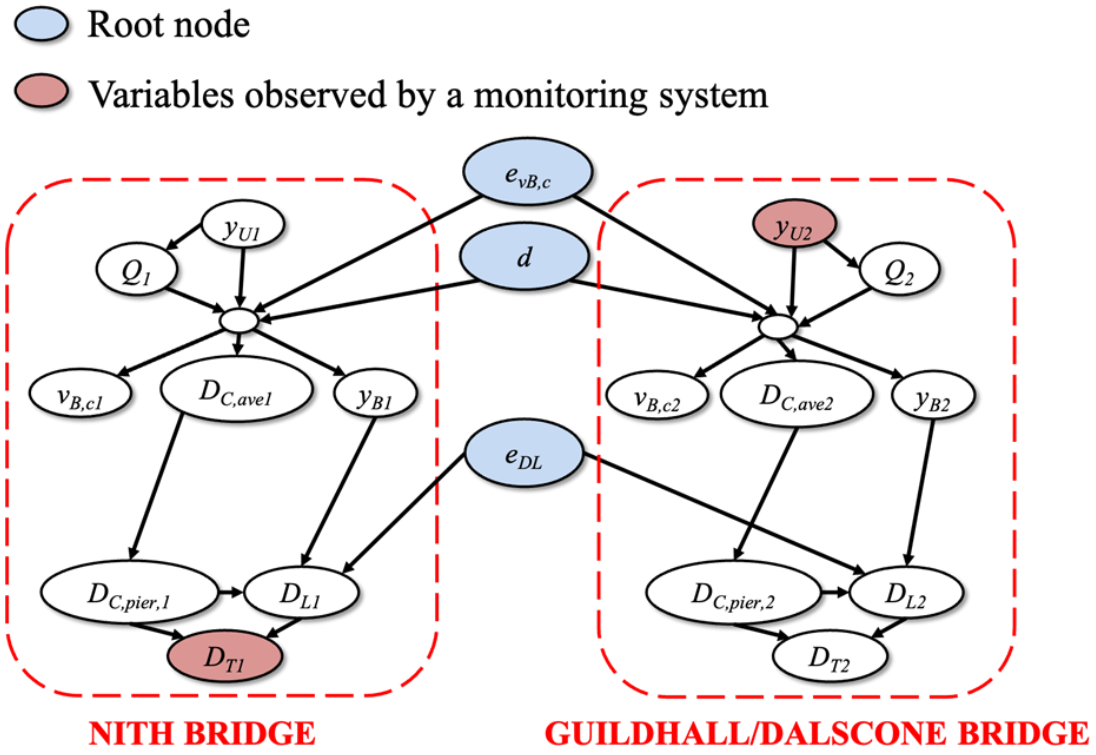
- The marker is **fixed** (e.g. 200 yrs return period flood)
- Water level is **very rough indicator** of the scour risk
- **No** direct considerations of consequences

OUR PROPOSAL

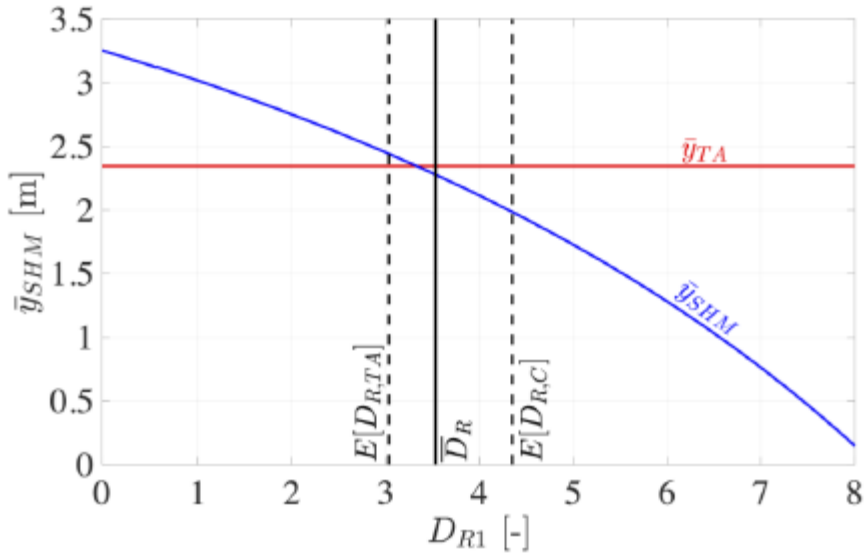
- **Adaptive marker**
- Calculated using **data** by scour sensor devices and water level sensors
- Consequences taken into account in taking decisions.

- **Rationale**: Knowledge of the actual scour depth at bridge foundations is characterised by significant uncertainty. Thus, the reduction of the uncertainty brought by sensor observations should also yield more accurate estimates of the water levels triggering bridge closure.

DECISION SUPPORT SYSTEM



Adaptive threshold at Guildhall bridge

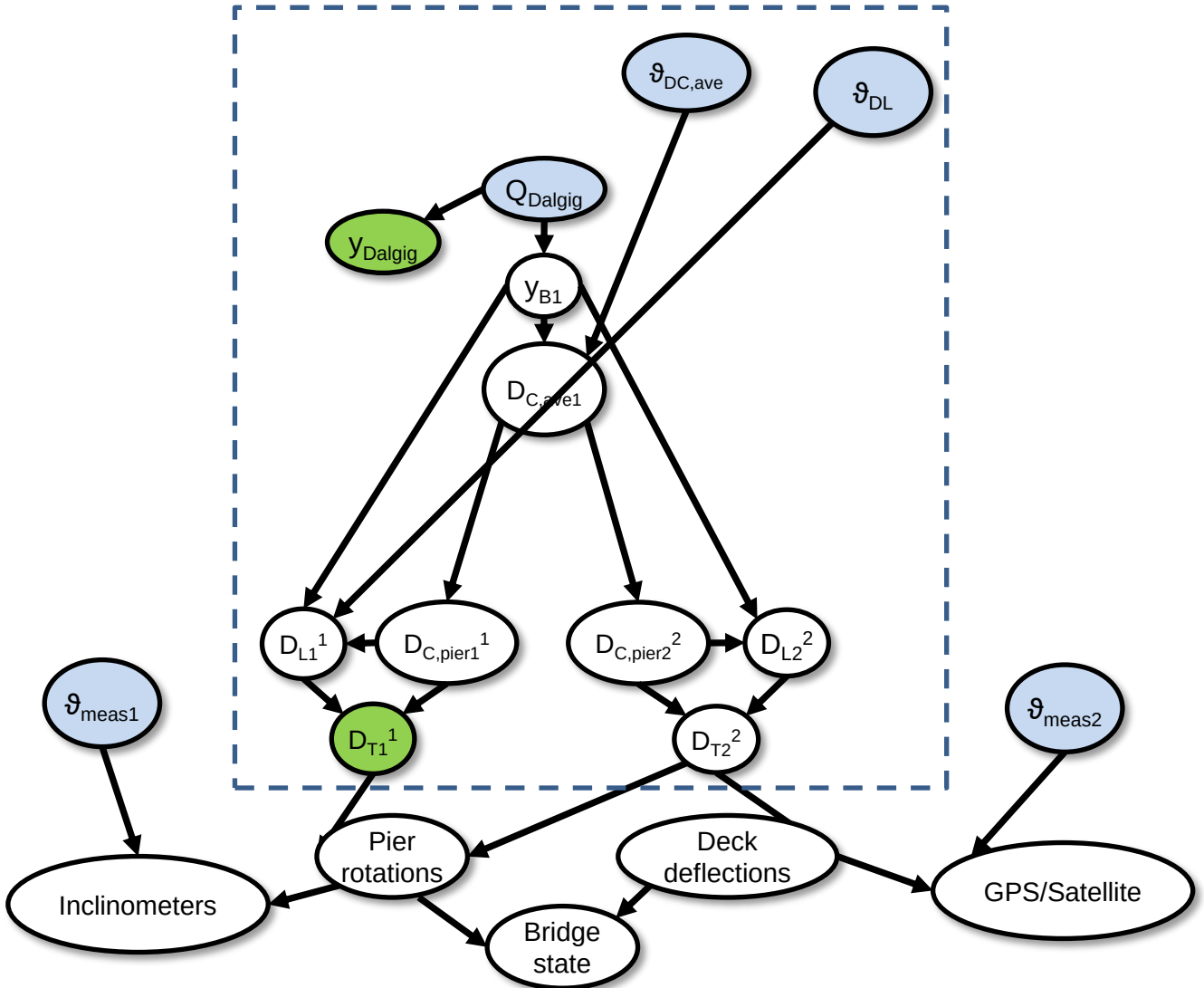


y_{TA}: current flood level marker

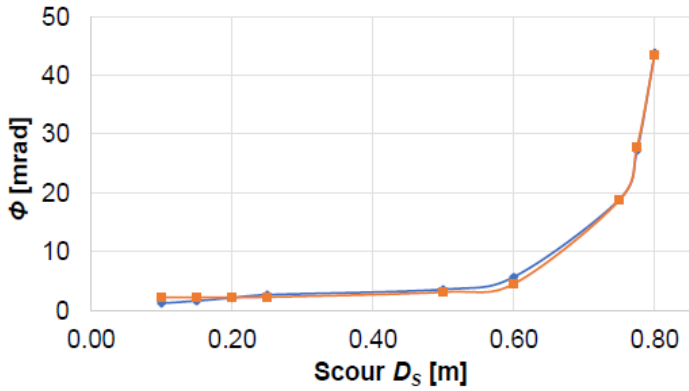
y_{SHM}: adaptive monitoring-informed flood level marker

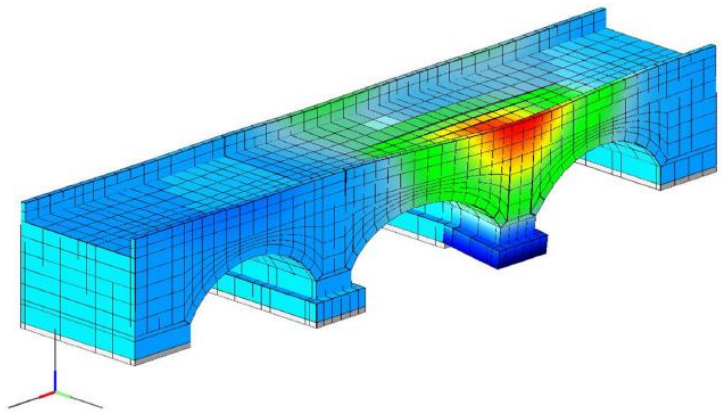
BN EXTENSION

- To include input from inclinometers, total stations, GPS antennas, satellites, accelerometers



Example of model relating scour depth to effects in terms of pier rotations





BN EXTENSION

$$\eta = \sqrt{\frac{\sigma_\theta^2}{\sigma_{\theta,PP}^2}} = \frac{\sigma_\theta}{\sigma_{\theta,PP}}$$

Ratio between prior and pre-posterior standard deviation of scour estimate

Scenario	Observation	Observation source	Nith	Bridge	Guildhall Bridge	Dalscone Bridge
			Pier 1	Pier 2	Pier 1	Pier 1
1 SEPA: 2.047 m, 3.521 m, 3.106 m	Probe μ: 0.90 m, 1.60 m Tilt μ: 5 mrad GPS μ: 36.8 mm	SEPA	1.234	1.182	1.236	1.199
		Probe+SEPA	-	4.099	3.743	3.547
		Tilt	3.833	2.258	2.030	2.037
		GPS	2.934	1.888	1.840	1.779
		Tilt+SEPA	3.965	2.845	2.693	2.706
		GPS+SEPA	2.938	2.167	2.296	2.295

REFERENCES

- **Maroni, A.**, Tubaldi, E., McDonald, H., & Zonta, D. (2023). Monitoring-based adaptive water level thresholds for bridge scour risk management. *Reliability Engineering & System Safety*, 109473.
- **Tubaldi, E.,** White, C. J., Patelli, E., Mitoulis, S. A., De Almeida, G., Brown, J., ... & Zonta, D. (2022). Invited perspectives: Challenges and future directions in improving bridge flood resilience. Natural Hazards and Earth System Sciences, 22(3), 795-812.
- **Tubaldi, E.,** Antonopoulos, et al. (2022). Field tests and numerical analysis of the effects of scour on a full-scale soil–foundation–structural system. Journal of Civil Structural Health Monitoring, 1-21.
- Antonopoulos, C., **Tubaldi, E.,** Carbonari, S., Gara, F., & Dezi, F. (2022). Dynamic behavior of soil-foundation-structure systems subjected to scour. Soil Dynamics and Earthquake Engineering, 152, 106969.
- Maroni, A., **Tubaldi, E**., Val, D. V., McDonald, H., & Zonta, D. (2020). Using Bayesian networks for the assessment of underwater scour for road and railway bridges. Structural Health Monitoring, 1475921720956579.
- Pizarro, A., Manfreda, S., & **Tubaldi, E**. (2020). The science behind scour at bridge foundations: A review. Water, 12(2), 374.
- Maroni, A., **Tubaldi, E.**, Ferguson, N., Tarantino, A., McDonald, H., & Zonta, D. (2020). Electromagnetic sensors for underwater scour monitoring. Sensors, 20(15), 4096.
- **Tubaldi, E.**, Maroni, A., Ferguson, N. and Zonta, D. (2020) Evaluating the benefit of structural health monitoring for improving bridge resilience against scour. Deliverable D1 – Report on critical review of alternative techniques for bridge scour monitoring. Documentation. National Centre for Resilience.
- Pizarro, A., & **Tubaldi, E.** (2019). Quantification of modelling uncertainties in bridge scour risk assessment under multiple flood events. Geosciences, 9(10), 445.
- **Tubaldi, E.,** Macorini, L., & Izzuddin, B. A. (2018). Three-dimensional mesoscale modelling of multi-span masonry arch bridges subjected to scour. Engineering Structures, 165, 486-500.
- **Tubaldi, E.,** Macorini, L., Izzuddin, B. A., Manes, C., & Laio, F. (2017). A framework for probabilistic assessment of clear-water scour around bridge piers. Structural safety, 69, 11-22.

Bridge scour - Projects

- FRAMAB Marie Curie project (2015-17)
- NERC project (2017-18)
- SERA EU project “DYMOBRIS” (2019-20)
- Scottish Road Research Board (2020-21)
- National Centre for Resilience (2020-21)
- Carnegie Trust Vacation scholarship (2020-21)
- Department for Transport (2022)
- Royal Society Research Grants (2022-23)
- National Highways (2023-24)
- ERIES EU project SCOUR & SHAKE(2023-24)

ERMABI Workshop – Exploiting the Resilience of Masonry Arch Bridge Infrastructure

University of Strathclyde Glasgow

Risk assessment and monitoring of masonry bridges exposed to scour

Enrico Tubaldi – Reader in Structural Engineering
University of Strathclyde, Glasgow, UK

06 Sept 2023

enrico.tubaldi@strath.ac.uk