University of BRISTOL

CHALLENGES AND PERSPECTIVES FOR INTEGRAL BRIDGES IN THE UK AND EUROPE: EXPERIMENTAL CAMPAIGNS AT THE UNIVERSITY OF BRISTOL

Flavia De Luca
Associate Professor of Structural and Earthquake Engineering

Academic Colleagues and Collaborators

Dr Sha Luo
University of Birmingham

Ziyan Huang, Yazan Asia, Raffaele De Risi, John Harkness, Louis Le Pen, Geoff Watson, David Milne, David Chapman, Anastasios Sextos, Nicole Metje, George Mylonakis, Nigel Cassidy, Ian Jefferson, Joel Smethurst, David Richards, Colin Taylor, William Powrie, Christopher D.F. Rogers

PLEXUS PLUS

Technical team @SoFSI – David Williams, Tony Horseman, Rainaa Ahmed
Technical team @Heavy and Light – Steve Harding, Guy Pearn, Peter Whereat
Technical Team @Equals – Simon Ball, Mictroy Mitchell

Dr Gabriele Fiorentino
University of Bristol, Roma Tre

bristol.ac.uk

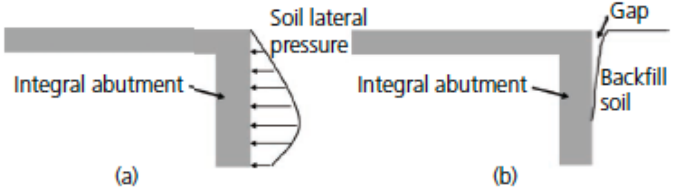
Cihan Cengiz, George Mylonakis, Dimitris Karamitros, Matt Dietz, Luiza Dihoru, Davide Lavorato, Bruno Briseghella, Tatjana Isakovic, Christos Vrettos, Antonio Topa Gomes, Anastasios Sextos, Camillo Nuti

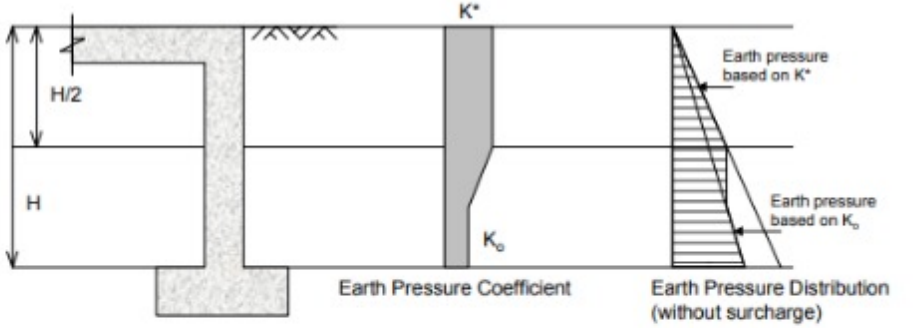
Why Integral Bridges

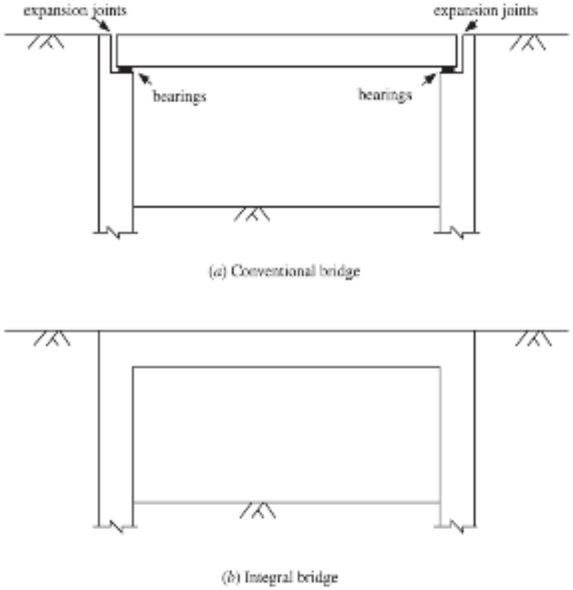
- No bearings to replace – lower life costs
- Limited spans and skews
- Not “allowed” in seismic areas
- How do we expand the scope and reduce the cost of integral bridges?

- Longer spans
- Larger skews
- High speed rail interactions
- Seismic situations

Critical design aspects - temperature







Comparison of (a) a conventional bridge and (b) an integral bridge (Xu et al, 2007)

Integral Bridges in codes

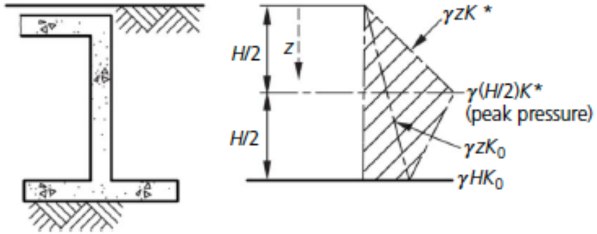


Figure 4. Earth pressure distributions for abutments that can accommodate thermal expansion by rotation and/or flexure (from BSI, 2011), where K_0 is the coefficient of earth pressure at rest; H is the vertical distance from the ground level to the level at which the abutment is assumed to rotate; γ is unit soil weight; z is the soil depth; and K^* is the design value of the earth pressure coefficient for expansion

Table 1. Summary information of design guidance

Design guidance	Region	Estimation of earth pressures	Limiting design criteria
Aashto (2012)	USA	The earth pressure coefficient variations are a function of structural displacement from experimental data and finite-element analyses, leading to a quasilinear relationship	The limiting design criterion varies in different states. In 1980, American Federal Highway Association recommended the following: steel bridge, 90 m; cast-in-place concrete bridge, 150 m; and post-tensioned bridges, 183 m.
Barker *et al.* (1991)		Limit equilibrium solutions based on log spiral failure mechanisms for standard backfill configurations (loose, medium and dense sand)	
Navfac (1982)		Limit equilibrium solutions based on log spiral failure mechanisms for standard backfill configurations (loose and dense sand)	
Navfac (1982)		Terzaghi's log spiral wedge theory to determine passive soil pressure coefficient[a]	
MassDOT (1999)		Provided the equations (according to full-scale wall tests) to calculate the design earth pressure distribution behind the abutment of IABs	
CGS (1978)	Canada	The soil pressure coefficients are based on the thermal movement of the model, varying with abutment rotation	Different provinces have their own design guidance. For example, Alberta limited the span of IABs to 100 m, with the skew angle less than 20°. Ontario limited the height of the abutment to 7 m and the length of the wingwall to 6 m.
BSI (2011)	UK	Limit equilibrium approach and SSI analysis	Span length, 60 m; skew, 30°; the characteristic thermal movement of the end of the deck is less than or equal to 40 mm.

[a] The log spiral theory was developed long before Terzaghi

Note that limit equilibrium methods cannot predict distributions of soil pressures with depth; hence, additional assumptions are needed to predict shear forces and bending moments along the wall

CGS, Canadian Geotechnical Society; IABs, integral abutment bridges; MassDOT, Massachusetts Department of Transportation; Navfac, Naval Facilities Engineering Systems Command

Integral Bridges monitored

Table 2. Summary information of monitored integral abutment bridges

Reference	Location	Span length: m	Skew: °	Height of abutment: m	Key monitoring findings
Barker and Carder (2000)	Manchester, UK	40	0	7	In the first 2 years of service, the measured lateral stresses increased
Barker and Carder (2001)	North Yorkshire, UK	50	Skewed	9	In the first 3 years of service, the measured lateral earth pressures increased slightly for each of the following summers
Hassiotis *et al.* (2005)	Trenton, NJ, USA	90.9	15	2.88	A steady build-up of soil pressures behind the abutment was observed
Breña *et al.* (2007)	Millers River, USA	82.3	0	3.05	The peak earth pressure at 2.5 m from the abutment top was observed to increase annually
Skorpen *et al.* (2018)	Van Zylspruit River, South Africa	90.45	0	6.6	In the first of year of service, a maximum earth pressure significantly (~1.75 times) higher than the at-rest pressure

IBs experiments

Table 3. Dimensions of available model tests

Model	*h*: mm	Test type	Aspect ratio				Abutment material	Backfill material	Constraint abutment
			w/h	*t/h*	*h/H*	*L/h*			
England *et al.* (2000)	570	1*g* pseudo-static	0.53	0.035[a]	1	2	Metal	Leighton Buzzard	Fixed-hinged
Springman *et al.* (1996)	110/115.9	60*g* centrifuge	1.88/162	0.099/0.085	0.45/0.53	2.9/2.5	Dural/steel	Dry sand	Embedded/spread-base
Cosgrave and Lehane (2003)	1000	1*g* pseudo-static	0.3	0.025	1	2.61	Mild steel plate	Dry siliceous sand	Hinge
Lehane (2011)	160/200	(20.0, 25.0, 37.5, 40.0)*g* centrifuge	0.8/1	0.1/0.08	0.65/1	3.19/2.55	Aluminium	Fine sand/glass ballottini/high-OCR kaolin	Hinge

[a] Estimation from the diagram proposed in the paper
H, height; *h*, height; *L*, length of the backfill; OCR, overconsolidation ratio; *t*, thickness of the abutment; *w*, width

Plexus experimental campaign

Stiffness properties of moveable walls S1, S2 and S3.

Moveable/Abutment Wall ID	Elastic modulus, E, (MPa)	A (mm^2)	I (mm^4)	EI (N^*mm^2)	$\rho^* = H^4/EI(m^3/kN)$	$L_m = H(E_s/EI)^{**}$
S1	1000	5.00E + 04	1.05E + 07	1.05E + 10	809E-4	18.3E-10
S2	1100	1.00E + 05	8.30E + 07	9.13E + 10	93.0E-4	2.10E-10
S3	23,491	1.12E + 05	11.8E + 07	277E + 10	3.06E-4	0.07E-10

*Rowe [58]; **mechanical length considering SSI (e.g., [59], where E_s = 20 MPa is the Elastic Modulus of the soil (see Table 5).

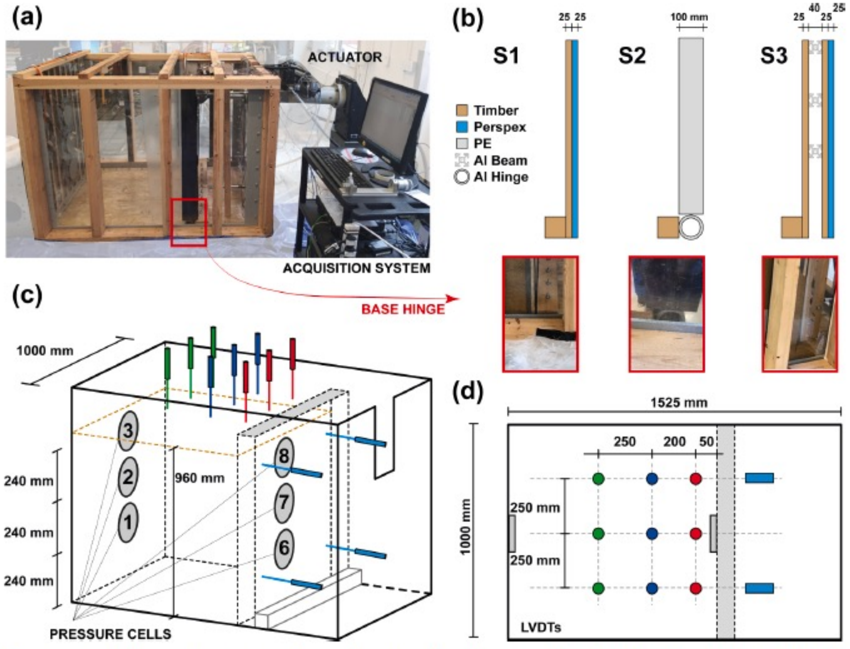
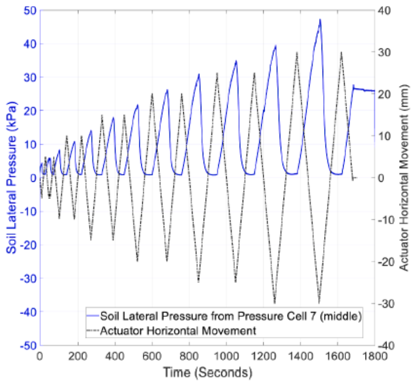
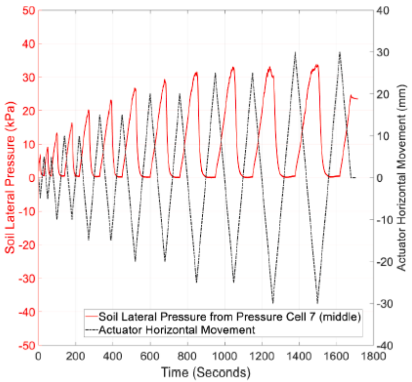


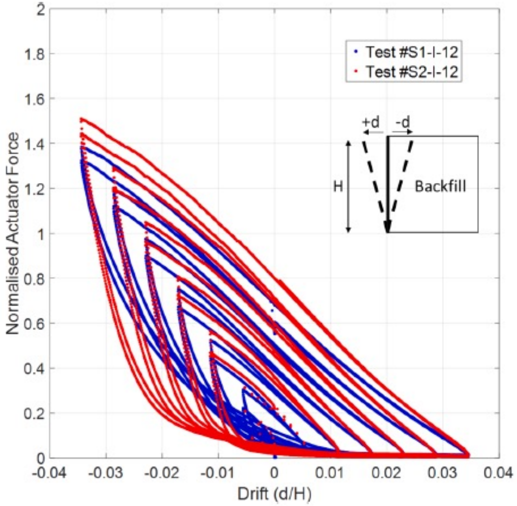
Fig. 1. (a) Photo of experimental setup including actuator and acquisition system; (b) section and size of the wall with S1, S2 and S3 stiffness; (c) location of pressure cells on the end of the wall (1–3) and moveable wall (6–8) and LVDTs; (d) top view of the test box identifying LVDT positions.

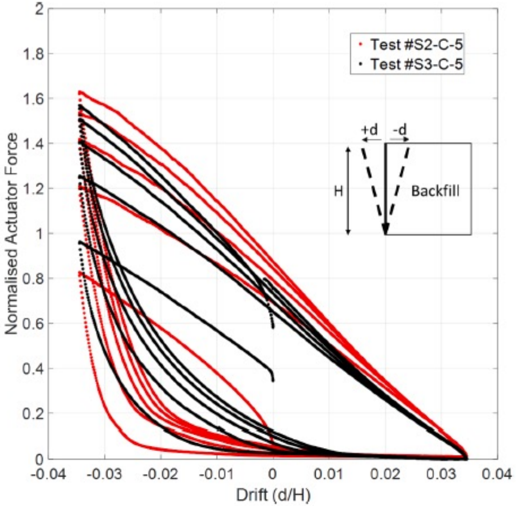
bristol.ac.uk

Plexus experimental campaign

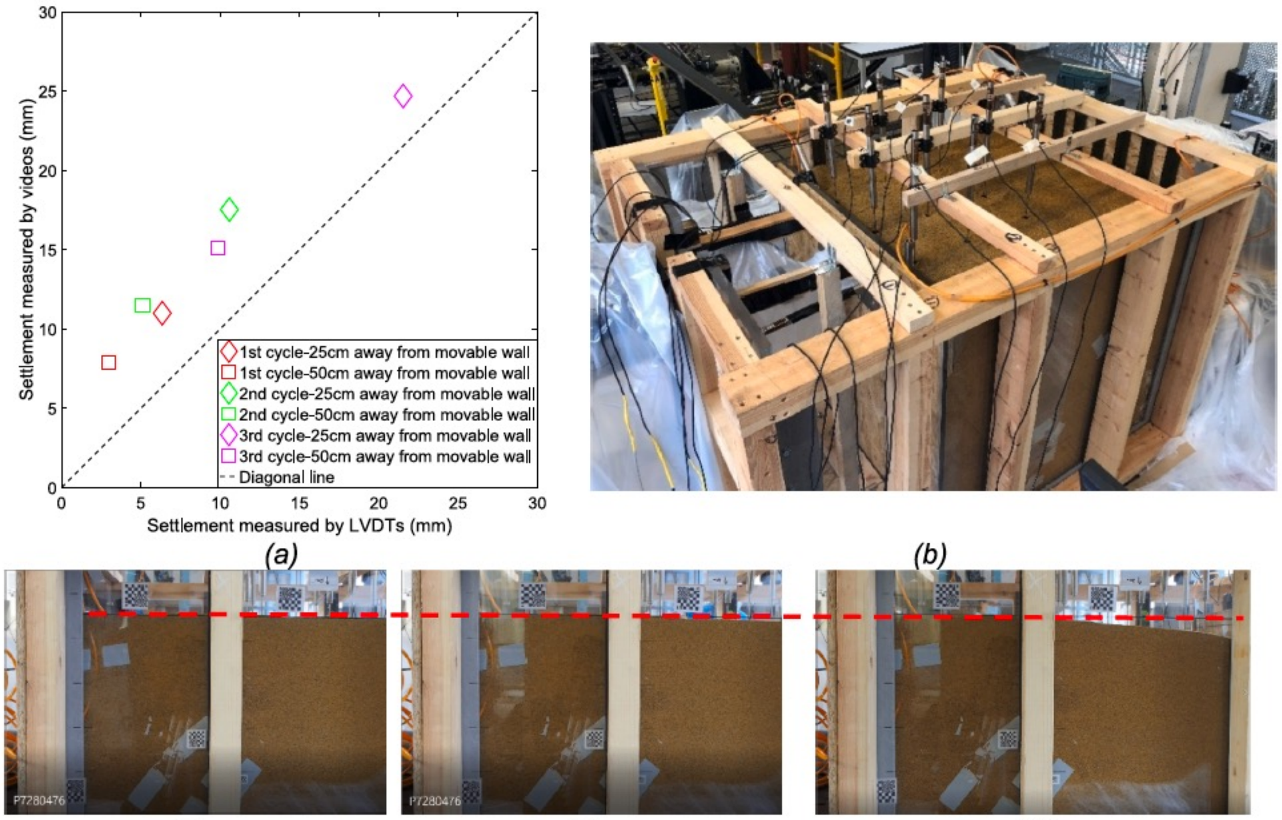








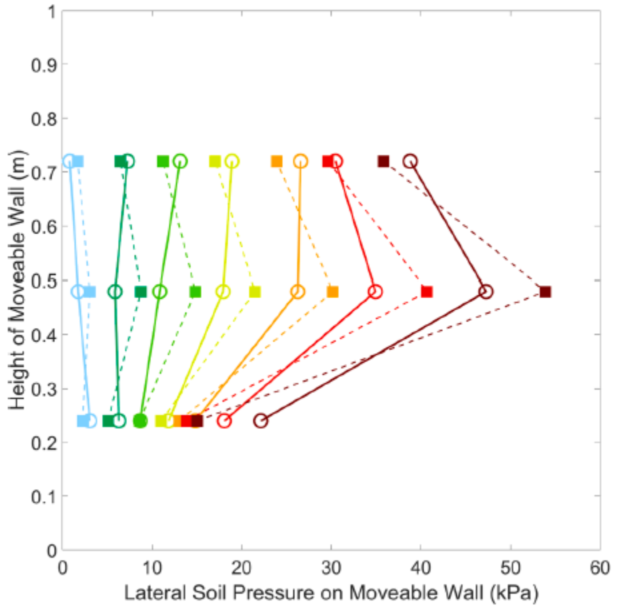
Plexus experimental campaign

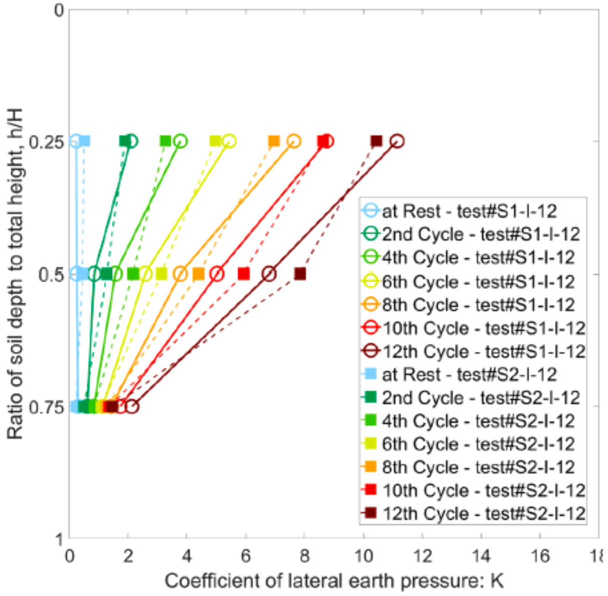


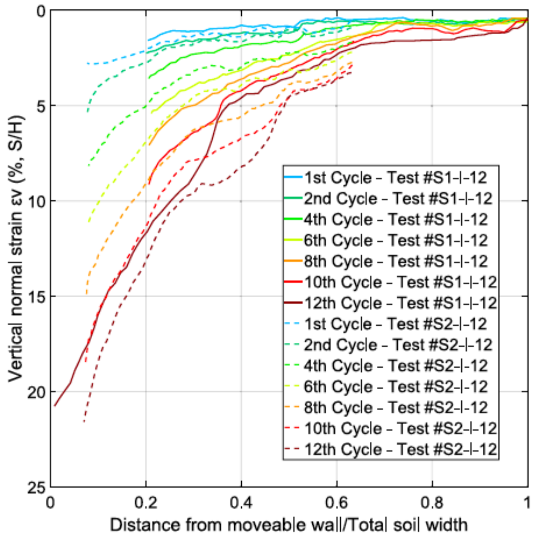
(c) (d) (e)

bristol.ac.uk

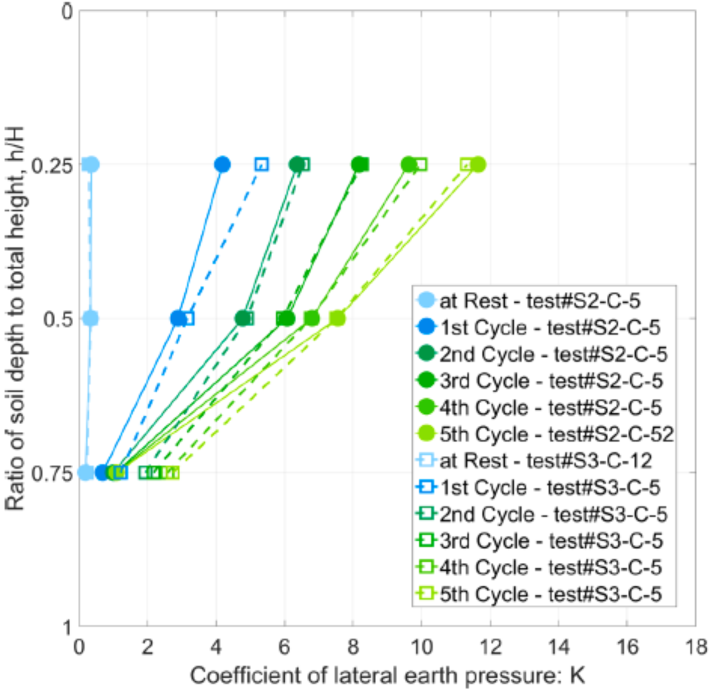
Plexus experimental campaign

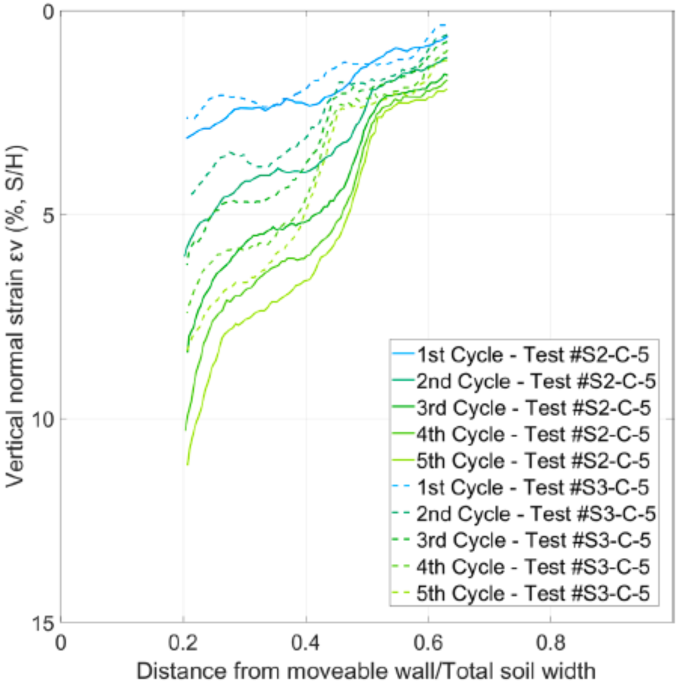






Plexus experimental campaign



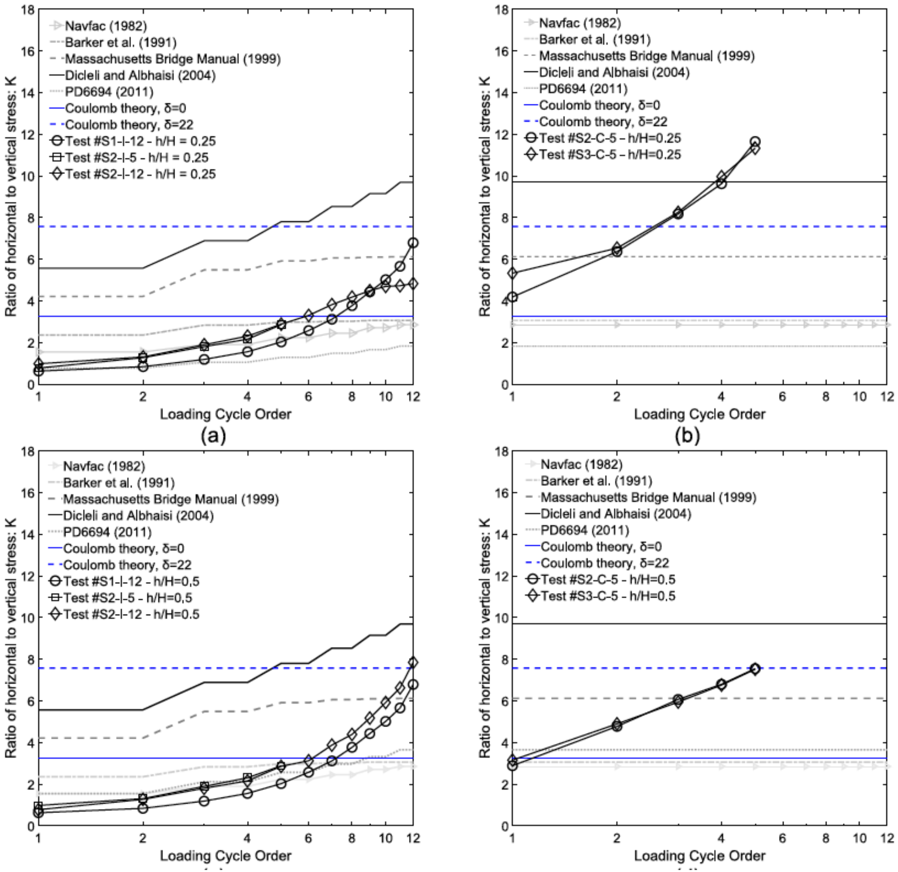


Plexus experimental campaign

Analytical formulations for the estimation of K in IABs depending on displacement.

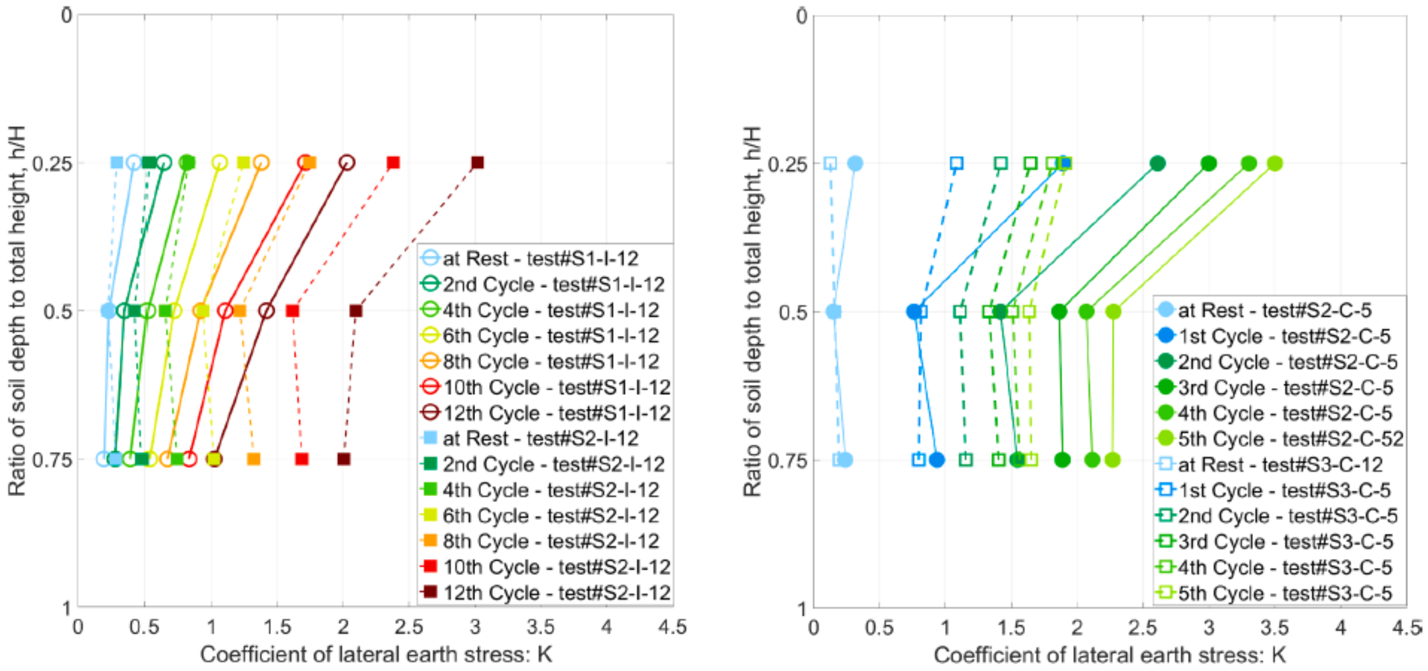
$K = 0.43 + 5.7\left[1 - e^{-190\left(\frac{d}{H}\right)}\right]$	*Massachusetts Bridge Manual, 1999*[69]
$K = K_0 + 28\left(\frac{d}{H}\right)^{0.33}$	Dicleli & Albhaisi (2004) [70]
$K_d^* = K_0 + \left(\frac{Cd_d'}{H}\right)^{0.6} K_{p;t}$	*PD 6694-1*[8]
$K = K_0 + \varnothing d \le K_p$	*Bal et al., 2018*[71]

Where d is the displacement of the IB towards the backfill soil; H is the height of the abutment; K_0 is the at-rest earth pressure coefficient; d_d' is the wall deflection at depth H/2 below ground level; C is a dimensionless coefficient equal to 20 for foundations on loose soils with Young's modulus $E \le 100$ MPa, and 66 for foundations on rock or soils with $E \ge 1000$ MPa, and which may be determined by linear interpolation for values of between 100 MPa and 1000 MPa; $K_{p,t}$ is the coefficient of passive earth pressure used in the calculation of K_d^*; $\varnothing$ is the slope of the earth pressure variation with horizontal displacement (which varies with backfill type); K_p is the passive earth pressure coefficient given by the Rankine theory equal to $(1-\sin\phi)/(1+\sin\phi)$ where ϕ is the friction angle.

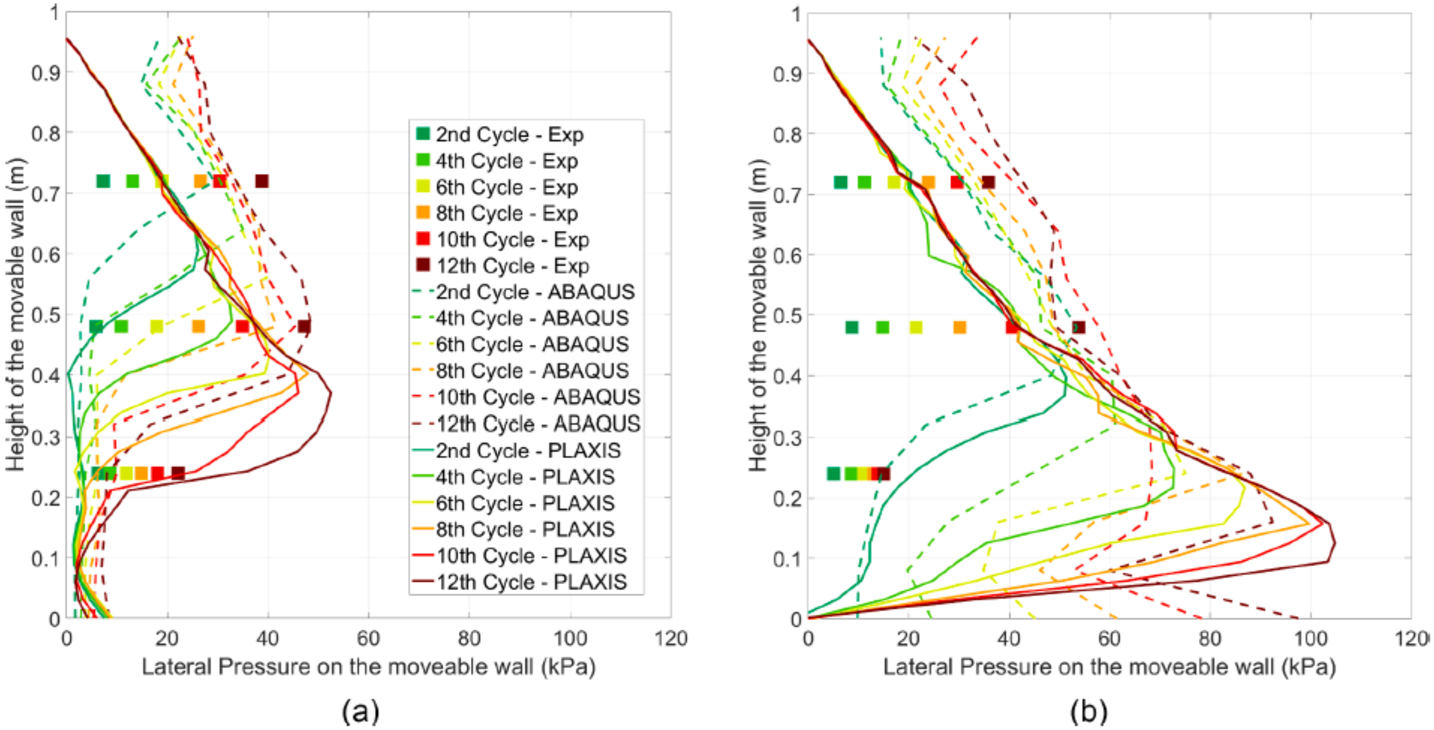


bristol.ac.uk

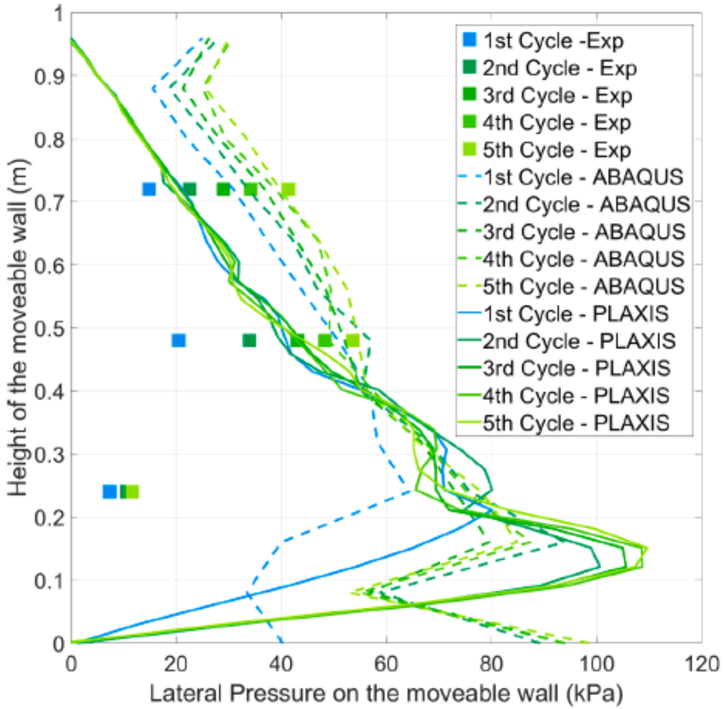
Plexus experimental campaign

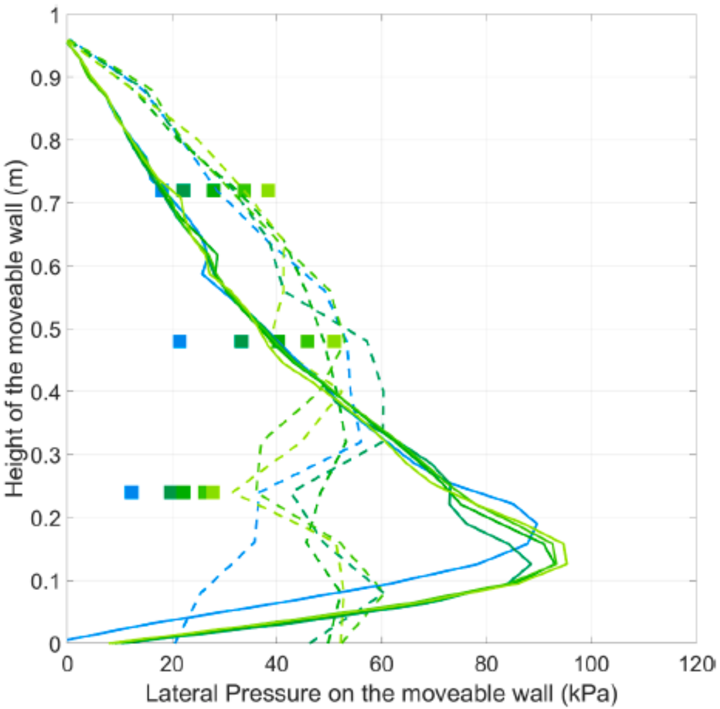


Plexus experimental campaign

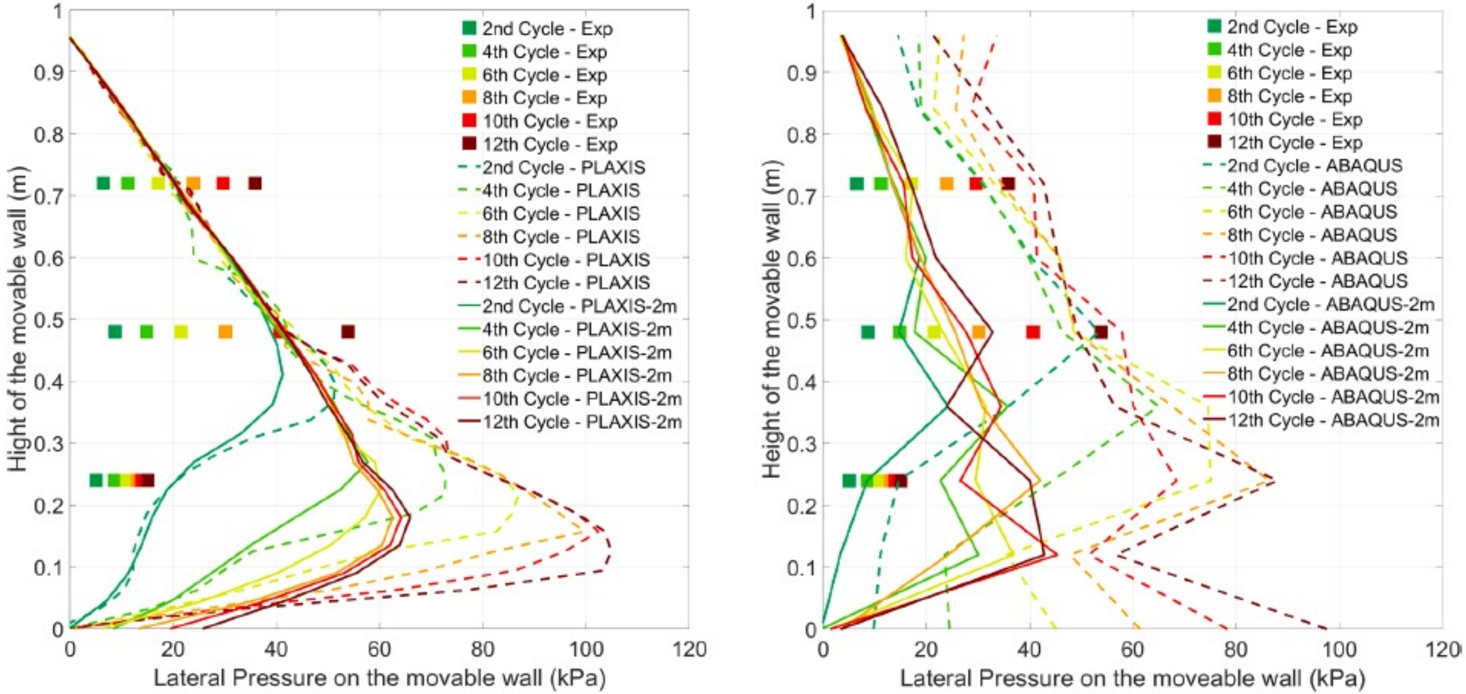


Plexus experimental campaign



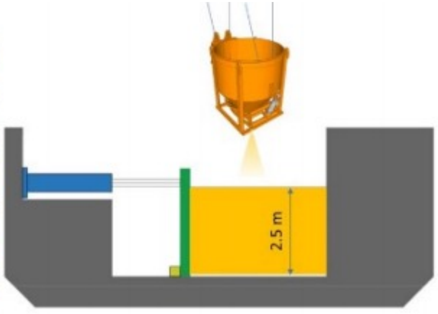


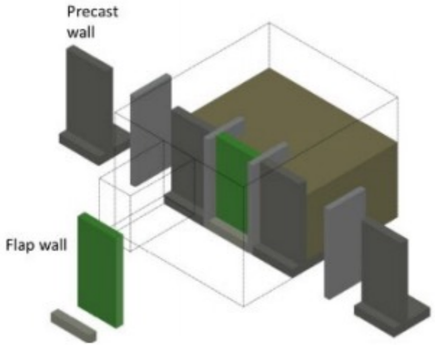
Plexus experimental campaign



Plexus plus experimental campaign

PLEXUS PLUS

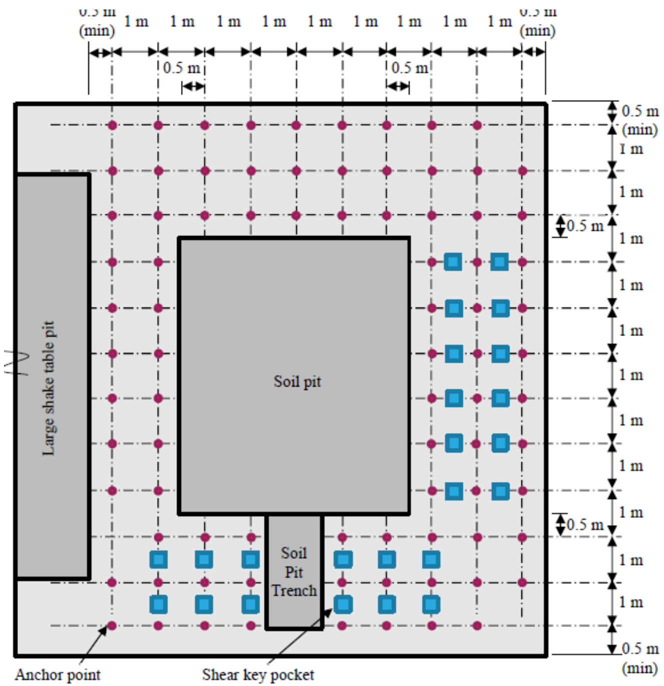


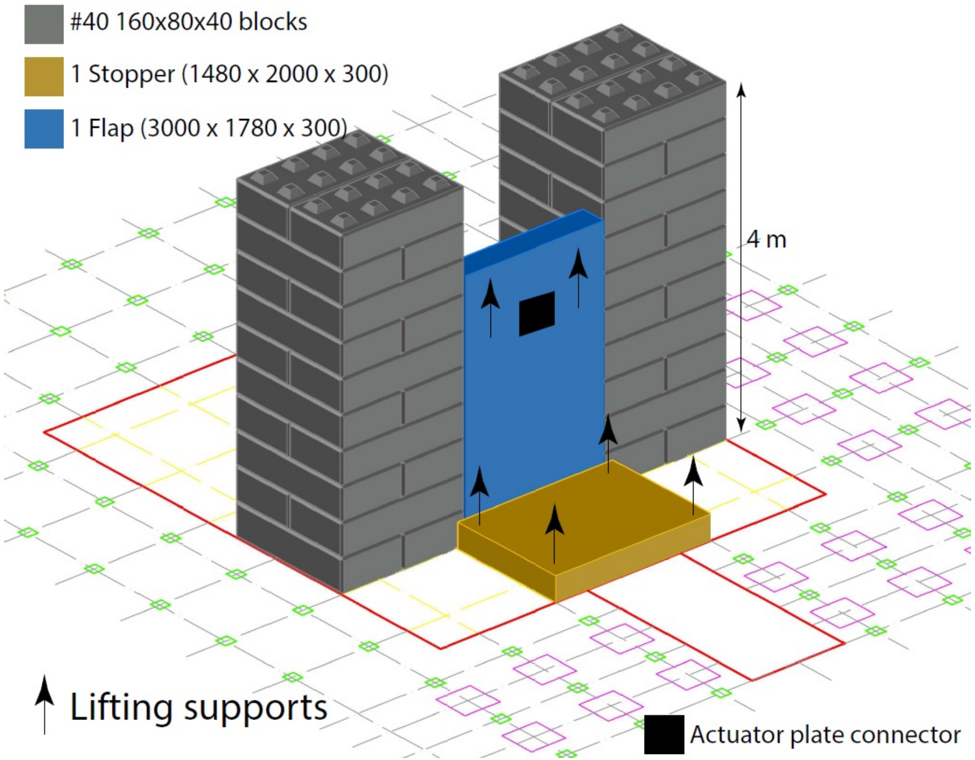


PI: Anastasios Sextos

Plexus plus experimental campaign

PLEXUS PLUS

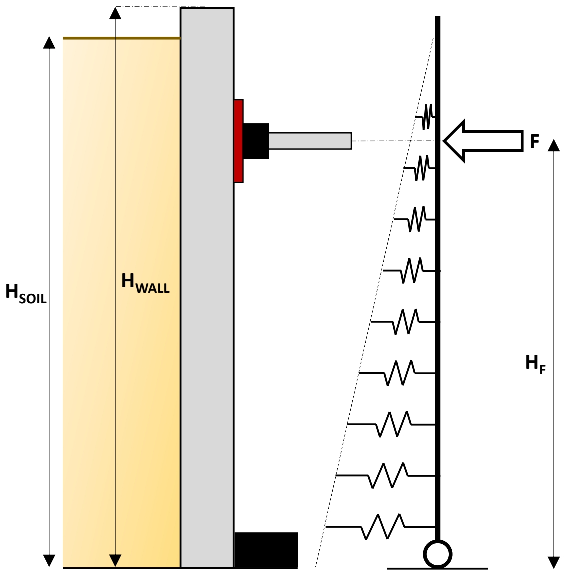


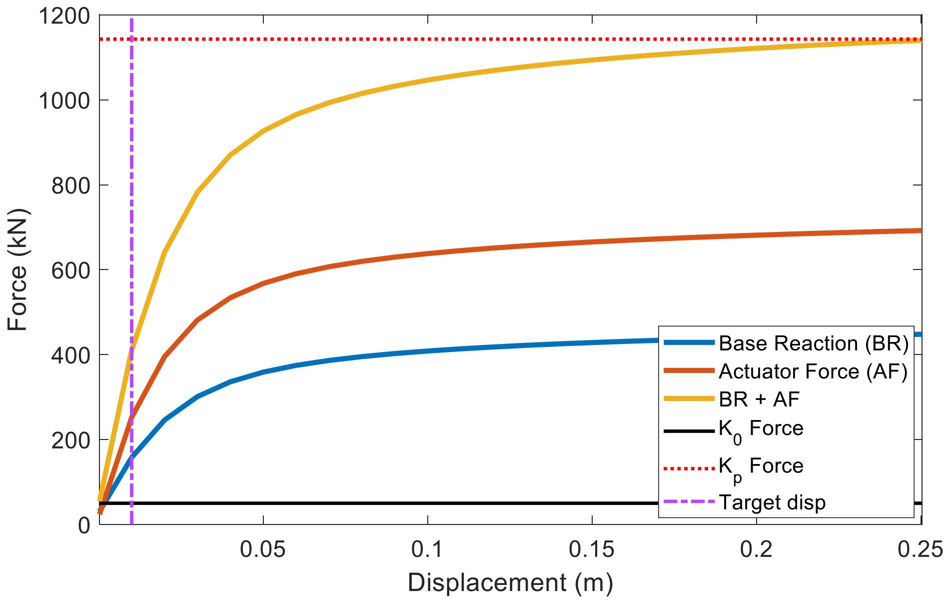


bristol.ac.uk

Plexus plus experimental campaign

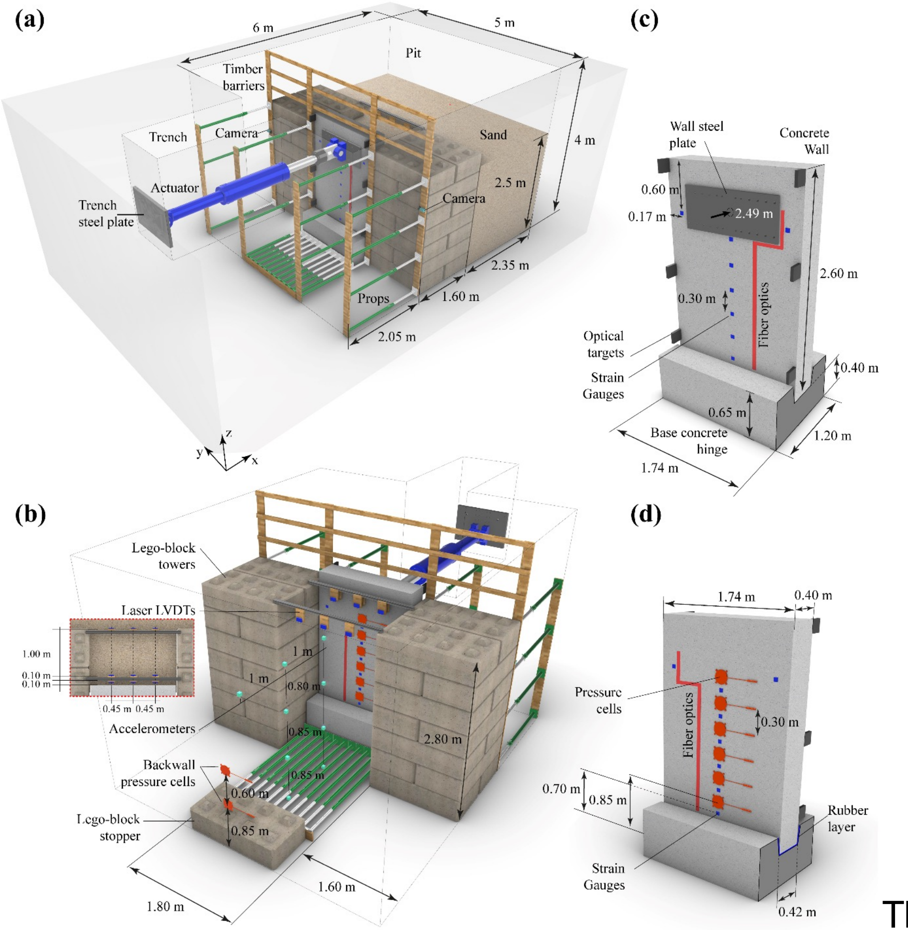
PLEXUS PLUS





Plexus plus experimental campaign

PLEXUS
PLUS



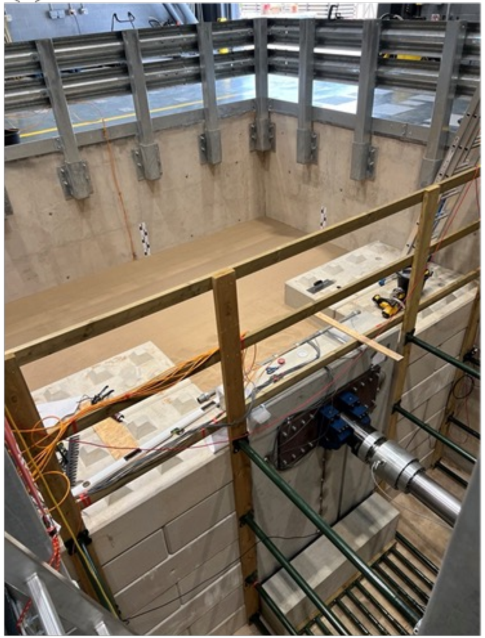
bristol.ac

Thanks to the @SoFSI technical team

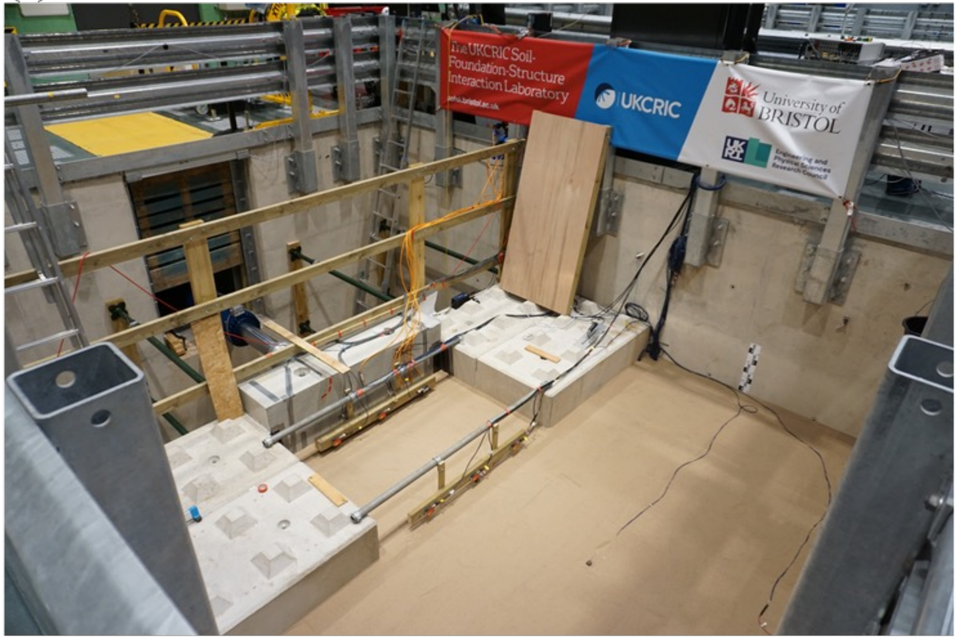
Plexus plus experimental campaign

PLEXUS
PLUS

(a)



(b)

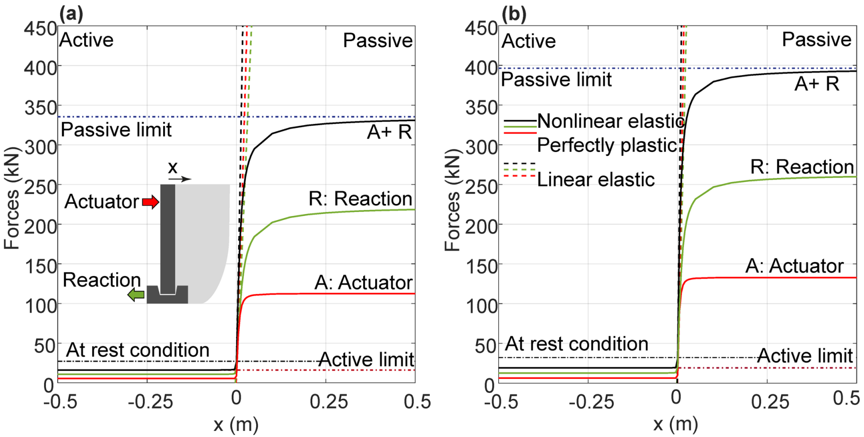


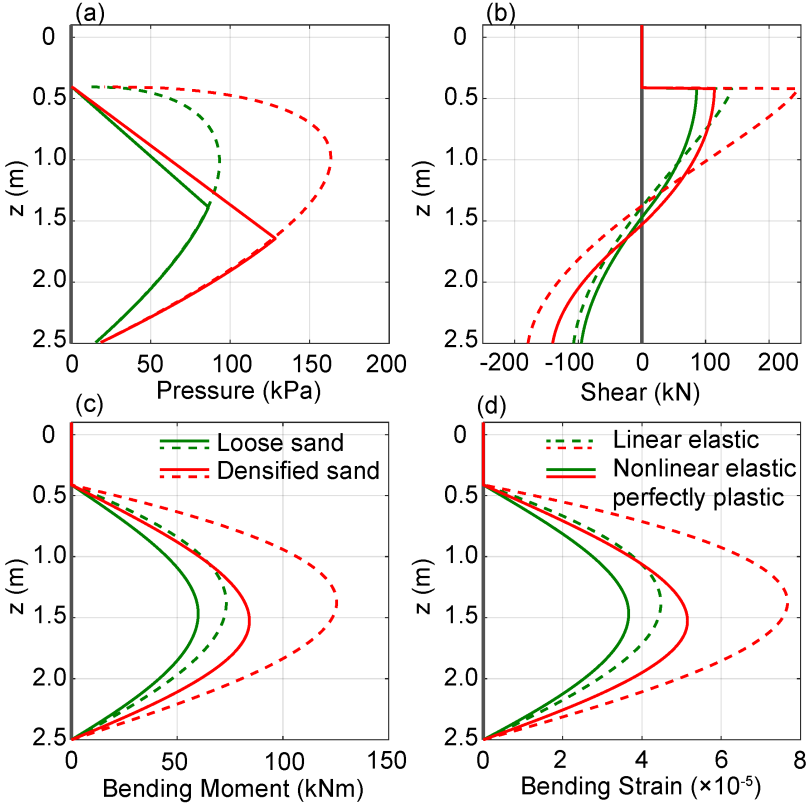
bristol.ac.uk

Thanks to the @SoFSI technical team

Plexus plus experimental campaign

PLEXUS PLUS

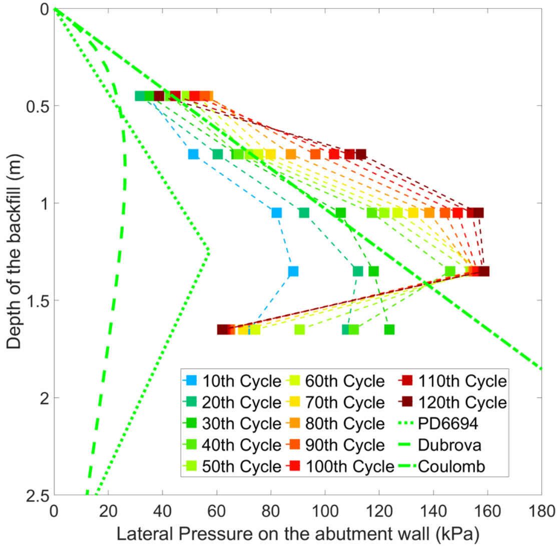


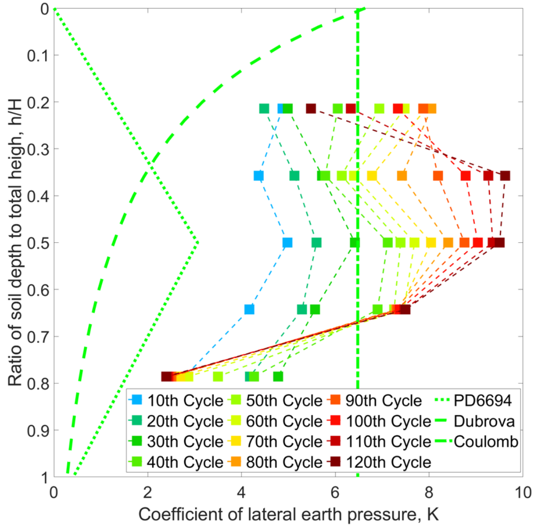


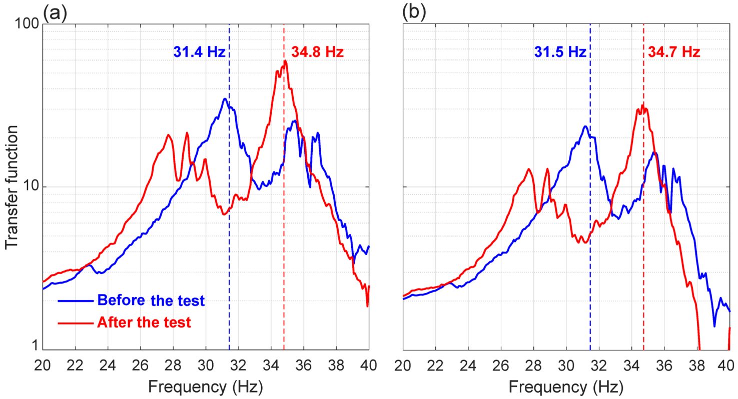
Thanks to Raffaele De Risi and George Mylonakis

Plexus plus experimental campaign

PLEXUS PLUS





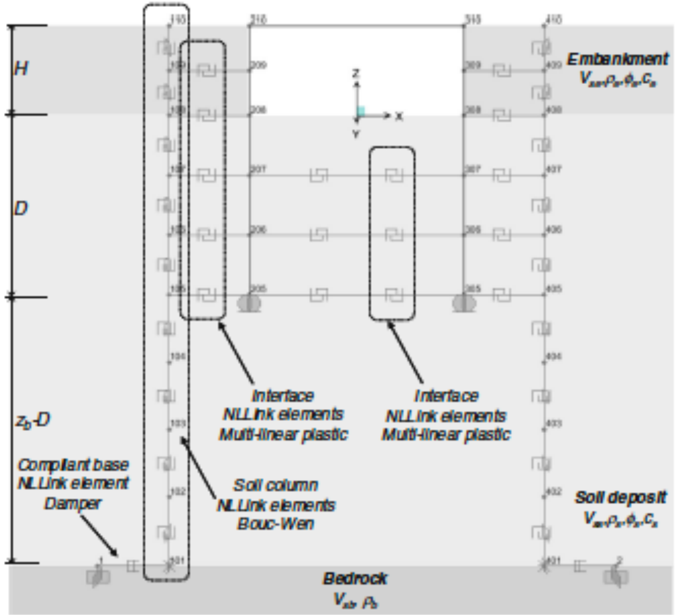


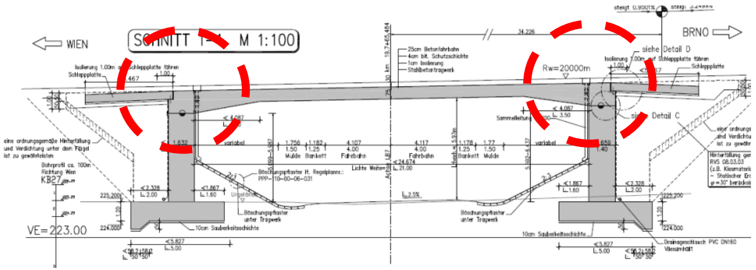
bristol.ac.uk

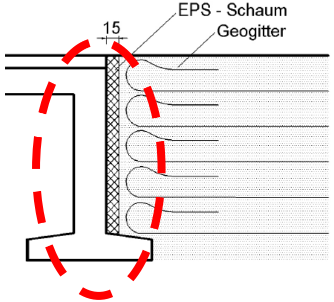
Thanks to Sha Luo

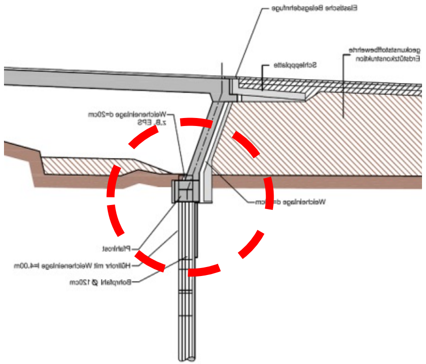
Critical design aspects - seismic

- Lack of experimental studies on Integral Abutment Bridges (IABs)
- Investigation on IAB response with a shaking table including SSI





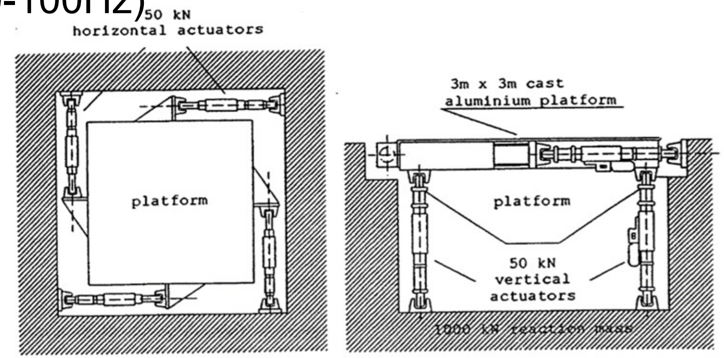




Compressible inclusion abutments/backfill **Disconnection of foundation piles**

SERENA experimental campaign

EQUALS-BLADE **Earthquake Simulator**: 3 x 3m cast aluminum platform (3.8 tons, maximum payload 15t,operational frequency 0-100Hz)



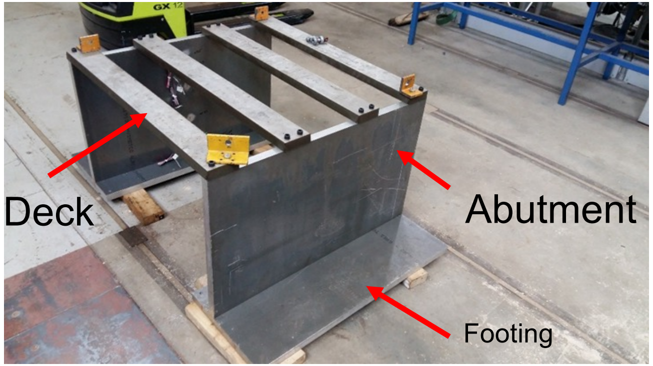
Empty **soil container**

- ❑ Length: 4.8 m
- ❑ Width: 1 m
- ❑ Height: 1.2 m

Soil container ready for testing

Bridge model

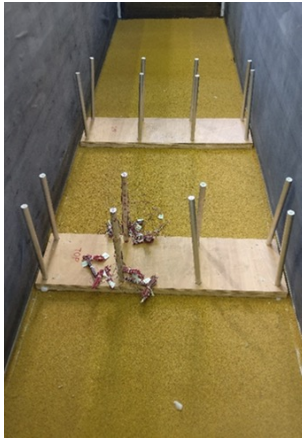
SERENA experimental campaign



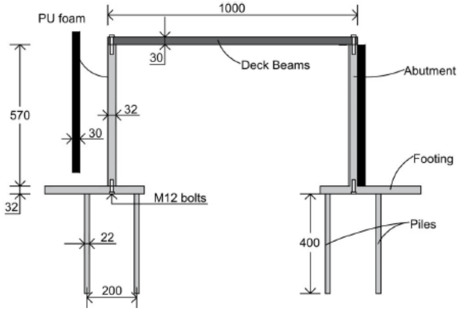
Abutment walls and footings: two 32 mm thick aluminum sheets

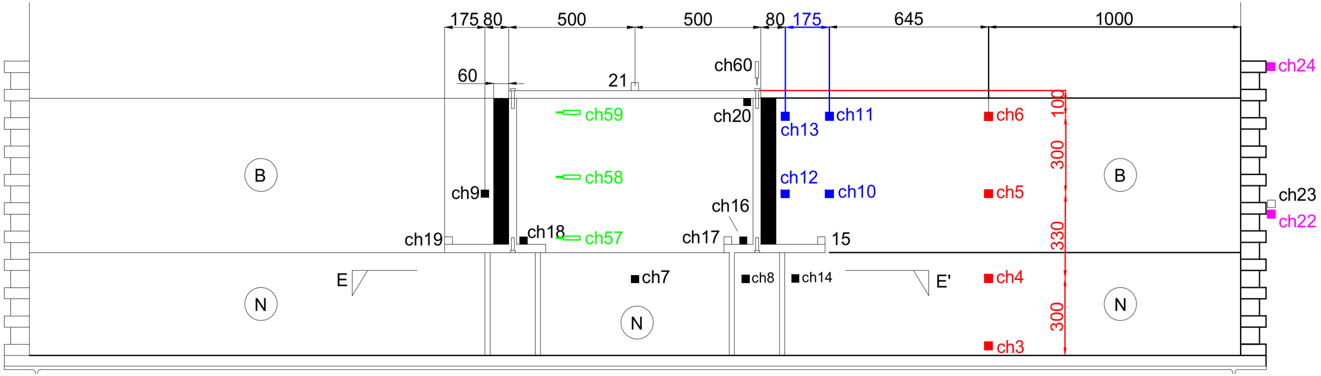
Bridge deck: four steel beams with L x W x D = 1000 x100 x 30 mm

- ❑ 16 aluminium hollow tubes were used as piles (d ≈ 22 mm)
- ❑ Piles inserted at the base into a plywood plate → vertical movements.
- ❑ **Nylon plug** at the top of each pile → "Connected Piles" config.



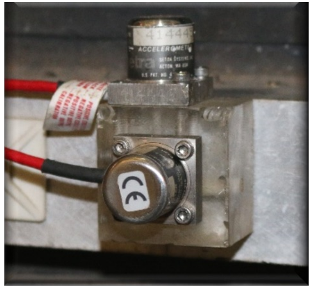
SERENA experimental campaign





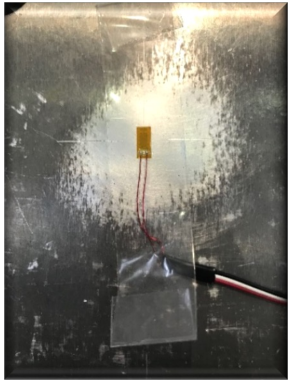
Accelerometers: n.24

- 6 Vertical
- 18 Horizontal



LVDT: n.4

Strain Gauges: n.32



bristol.ac.uk

SERENA experimental campaign

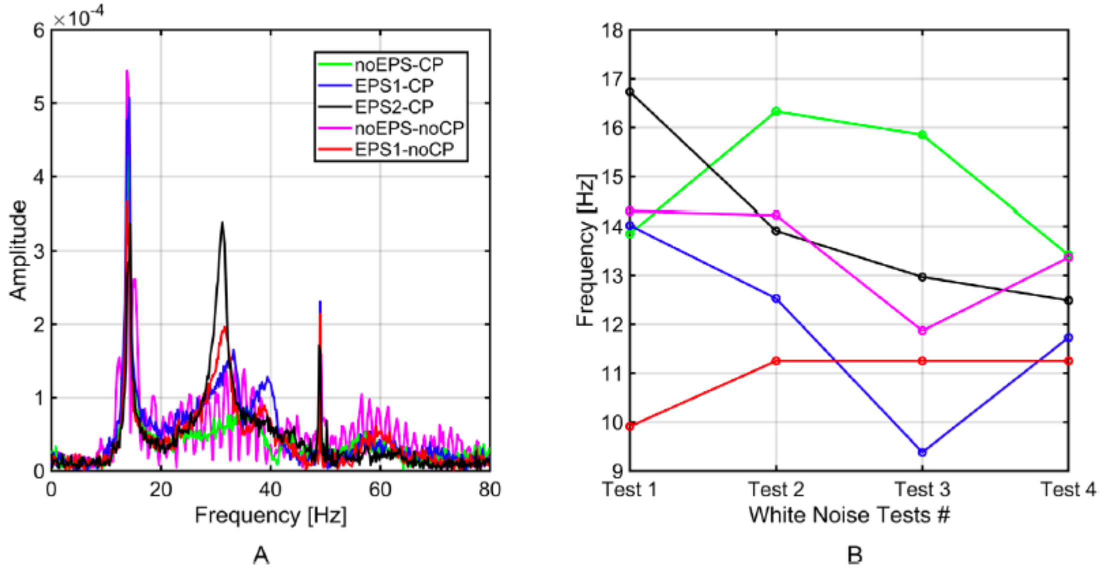


FIGURE 7 A, Frequency response for *EPS2-CP* in hammer tests, B, evolution of resonant frequency of all configurations determined through white noise tests *W1*, *W2*, *W3* and *W4* as recorded by accelerometer 22

SERENA experimental campaign

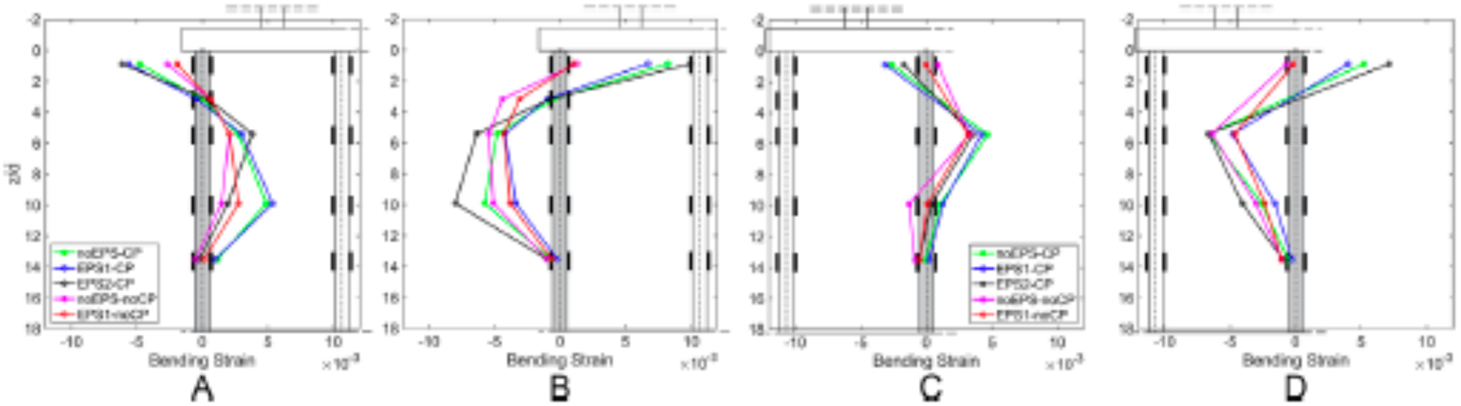


FIGURE 13 A, Maximum, and B, minimum pile bending strain on the East pile; C, maximum, and D, minimum pile bending strain on the West pile to *S7*

Final Remarks and Further Research

- Analytical tools for estimation of earth pressures in IABs are still very conservative
- Field monitoring can address the first phases but not the all-life span effects of SSI
- Experimental testing (even large scale) needs to account for scaling
- Some of the limitations, still present in codes, for IABs seem over conservative and need experimental-evidence to be reviewed
- Geotechnical isolation and other mitigation strategies (if controlled) can make a huge difference in terms of design

University of BRISTOL

ANY QUESTION?

flavia.deluca@bristol.ac.uk

Fiorentino G, Cengiz C, **De Luca F**, Mylonakis G, Karamitros D, Dietz M, et al. Integral abutment bridges: Investigation of seismic soil-structure interaction effects by shaking table testing. Earthq Eng Struct Dyn 2021;50(6):1517–38.

Luo S, **De Luca F,** De Risi R, Le Pen L, Watson G, Milne D, et al. Challenges and perspectives for integral bridges in the UK: PLEXUS small-scale experiments. Proc Inst Civil Eng - Smart Infrastruct Construct 2022;175(1):27–43.

Luo, S., Huang, Z., Asia, Y., **De Luca, F.**, De Risi, R., Harkness, J., ... & Rogers, C. D. (2023). Physical and numerical investigation of integral bridge abutment stiffness due to seasonal thermal loading. Transportation Geotechnics, 42, 101064.