# DECK POUNDING ON THE ABUTMENT-BACKWALL SYSTEM OF BRIDGES: THE ERIES-POUNDBAC$^2$ PROJECT

A. Kappos[1], C. Demartino[2], F. De Luca[3], D. Karamitros[4], R. De Risi[5], E.G. Dimitrakopoulos[6], Mehyar Abu Shehab, H.[7], R. Di Laora[8], A. Crewe[9], M. Dietz[10], T. Horseman[11], B. Briseghella[12], D. Lavorato[13], T. Isakovic[14], A. Sextos[15], G. Mylonakis[16] and C. Nuti[17]

[1] Department of Civil Infrastructure and Environmental Engineering, Khalifa University, Abu Dhabi, United Arab Emirates, andreas.kappos@ku.ac.ae

[2] Department of Architecture, Roma Tre University, Rome, Italy, cristoforo.demartino@uniroma3.it

[3] Department of Civil Engineering, University of Bristol, Bristol, United Kingdom, flavia.deluca@bristol.ac.uk

[4] Department of Civil Engineering, University of Bristol, Bristol, United Kingdom, d.karamitros@bristol.ac.uk

[5] Department of Civil Engineering, University of Bristol, Bristol, United Kingdom, raffaele.derisi@bristol.ac.uk

[6] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong, Hong Kong, ilias@ust.hk

[7] Department of Civil Infrastructure and Environmental Engineering, Khalifa University, Abu Dhabi, United Arab Emirates, 100059878@ku.ac.ae

[8] Department of Engineering, Universitá della Campania - Luigi Vanvitelli, Aversa, Italy, raffaele.dilaora@unicampania.it

[9] Department of Civil Engineering, University of Bristol, Bristol, United Kingdom, a.j.crewe@bristol.ac.uk

[10] Department of Civil Engineering, University of Bristol, Bristol, United Kingdom, m.dietz@bristol.ac.uk

[11] Department of Civil Engineering, University of Bristol, Bristol, United Kingdom, tony.horseman@bristol.ac.uk

[12] Dept. of College of Civil Engineering, Fuzhou Univ., Fuzhou, China, bruno@fzu.edu.cn

[13] Department of Architecture, Roma Tre University, Rome, Italy, davide.lavorato@uniroma3.it

[14] Faculty of Civil and Geodetic Engineering, University of Ljubljana Ljubljana, Slovenia, tatjana.isakovic@ikpir.fgg.uni-lj.si

[15] Department of Civil Engineering, University of Bristol, Bristol, United Kingdom and National Technical University of Athens, Greece, a.sextos@bristol.ac.uk

[16] Department of Civil Infrastructure and Environmental Engineering, Khalifa University, Abu Dhabi, United Arab Emirates and Department of Civil Engineering, University of Bristol, Bristol, United Kingdom, g.Mylonakis@bristol.ac.uk

[17] Department of Architecture, Roma Tre University, Rome, Italy, camillo.nuti@uniroma3.it

**Abstract**: *A challenging aspect of the seismic response of bridges is the phenomenon known as "pounding" i.e., the collision between the deck and the seat-type abutment and/or between adjacent deck segments in bridges with internal joints. While extensive research has been conducted on pounding effects in buildings, studies on bridges, particularly those incorporating large-scale experimental investigations, remain relatively limited. The ERIES project 'Pounding on Backwall-backfill Systems (PoundBac$^2$)' aims to address this critical gap in knowledge through a pioneering experimental campaign, i.e., the world's first comprehensive testing of the effects of deck pounding on the abutment-backwall system in bridges with seat-type abutments. This ground-breaking initiative is expected to provide valuable experimental data that will significantly broaden our understanding of the behaviour of these systems under seismic loads and inform and improve future bridge design practices. The experimental tests are scheduled to be carried out in spring 2024 at the state-of-the-art SoFSI-Soil Pit facility at Bristol University and results are expected to be available prior to the WCEE. The international research team is currently engaged in the refinement of the innovative experimental setup to investigate such a complex dynamic phenomenon. In this paper, we present a comprehensive overview of the ERIES-PoundBac$^2$ project, shedding light on the planned experimental tests and the anticipated outcomes. This paper serves as an initial exploration of the project's objectives, methodologies, and expected findings.*

## 1 Introduction

One challenging aspect of bridge engineering involves addressing the dynamic forces that bridges experience during seismic events (Miari *et al.*, 2021). In particular, in bridges with joints (intermediate or end) one of the phenomena that raise concern is pounding of adjacent parts of the bridge (between segments of the deck, or deck and abutment) at the location of the joints when the bridge is subjected to high-amplitude dynamic loading that induces significant velocities. There is ample evidence of pounding-induced damage in bridges during several earthquakes, such as those in San Fernando (USA, 1971), Loma Prieta (USA, 1989), Northridge (USA, 1994), Kobe (Japan, 1995) (Mylonakis and Gazetas, 2000), Chi–Chi (Taiwan, 1999), Yogyakarta (Indonesia, 2006), Wenchuan (China, 2008), Maule (Chile, 2010) and Christchurch (New Zealand, 2011) (Miari *et al.*, 2021).

Although the bulk of research on pounding effects concerned buildings (Jankowski and Mahmoud, 2015), pounding in bridges has also attracted some interest (Miari *et al.*, 2021), including primarily analytical/computational studies (e.g. (DesRoches and Muthukumar, 2002; Zhu *et al.*, 2002; DesRoches and Muthukumar, 2004; Guo *et al.*, 2015, Shi and Dimitrakopoulos, 2017), and, to a much lesser extent, experimental studies (DesRoches and Muthukumar, 2004; Saiidi *et al.*, 2013; Kun *et al.*, 2017); the latter include small-scale shaking table testing of bridge models. It is crucial in the context of this proposal that in the few studies involving testing of a bridge with seat type-abutments on which pounding of the deck occurred, the abutment system never included the embankment or even the backfill soil.

The existing literature highlights a clear research gap concerning the effect of pounding between bridge decks and the abutment-backfill system in bridges with seat-type abutments (Taskari and Sextos, 2015). To bridge this gap, there is a pressing need for large-scale testing of such systems subjected to simulated earthquake motions. These tests should encompass a portion of the abutment sufficient to capture the relative stiffness of the backwall and the stem wall, noting that, in most actual bridges, the latter's deformation is negligible compared to that of the former (Mikes and Kappos, 2021). Moreover, it is important to incorporate a significant section of the backfill in these tests, accurately replicating the stiffness and energy dissipation characteristics of this crucial component. Properly designed boundary conditions should also be implemented to prevent multiple reflections of waves within the backfill, a scenario that does not typically occur in actual structures. This research gap underscores the need for in-depth investigations to advance our understanding of the complexities involved in bridge pounding during seismic events.

In this context, this paper addresses a significant knowledge gap in structural engineering by focusing on the impact of bridge pounding during seismic events, focussing on bridges with seat-type abutments. Specifically, this paper describes the ERIES-PoundBac$^2$ project representing a ground-breaking endeavour, aiming to conduct the world's first comprehensive experiments to tackle this problem. These experiments, set to be caried out in spring 2024, will provide valuable insights into the effects of deck pounding on the abutment-backfill system of bridges with seat-type abutments, ultimately contributing to the advancement of bridge design and safety standards. The paper outlines the project's objectives, methodologies, and anticipated outcomes. The ERIES-PoundBac$^2$ research team expects to provide relevant experimental results during the presentation at the 2024 World Conference on Earthquake Engineering (18WCEE).

This paper delves into the critical issue of bridge pounding, focusing on seat-type abutments, and sets the stage for forthcoming experimental tests. Section 2 explores the distinctive characteristics of seat-type abutments and the main issues related to pounding. Section 3 details the planned experimental setup at the SoFSI-Soil Pit facility of Bristol University. Section 4 addresses the problem of deriving fundamental parameters of pounding and validating advanced models, while Section 5 includes a series of concluding remarks.

## 2 Seat-type abutments

Seat-type abutments (Figure 1) are commonly used in various bridge designs and are particularly prevalent in highway and road bridge construction. A critical component of the abutment-backfill system is the backwall, i.e., a joint between the abutment backwall and the superstructure providing a stress relief during thermal loadings (Wieser et al., 2012). In seismically designed bridges, the backwall is often designed with a view to protecting the remainder of the system, notably the foundation, as further discussed in the following.

*Figure 1. Schematic (left, from Shamsabadi et al. (2010)) and photo (from https://theconstructor.org/structures/bridge-abutment-seismic-retrofitting/17696/) of a typical seat-type abutment system.*

### 2.1 Seismic pounding and gap

When the bridge is subjected to seismic actions, the interaction between the bridge deck and the seat-type abutments becomes a critical point of consideration. During strong ground motion the expansion joint may close resulting in seismic pounding between the bridge deck and the abutment backwall. Seismic pounding has been identified as a significant cause of damage to seat-type abutments in various recent earthquake events. This is due to the fact that the large inertia forces generated in the superstructure may mobilize the active pressure in the backfill soil behind the abutment backwall which can result in nonlinear soil behaviour. Moreover, the backwall itself is heavily damaged and has to be retrofitted after the earthquake. Critical damage mechanisms related to abutment backwalls, as illustrated in Figure 2 (after Zheng *et al.* (2021)), have been observed during previous seismic events. For instance, during the 1971 San Fernando earthquake, severe damage to highway bridges was attributed to the closure of expansion gaps. Similarly, in the 1994 Northridge earthquake, substantial pounding damage was observed at the expansion joints of the I5/SR14 interchange near the epicenter. The 1995 Kobe earthquake also highlighted seismic pounding as a major contributor to damage in bearing supports, potentially playing a role in the collapse of bridge superstructures. Furthermore, the 1999 Chi Chi earthquake resulted in notable damage to shear keys, bearings, and anchor bolts, all of which were linked to the effects of pounding. These instances underscore the critical importance of addressing and mitigating the impact of seismic pounding.

*Figure 2. Examples of backwall damage: (left) punching of the Tubul bridge deck into the backwall, and (right) damage at the base of the abutment backwall of the El Bar bridge. After Zheng et al. (2021).*

### 2.2 Code provisions

As a rule, abutment backwalls in modern bridge designs are intentionally constructed as sacrificial components, engineered to fail before the bridge foundations. This approach aims to minimize forces in abutment foundations, thus avoiding the time-consuming process of foundation excavation and repair. This strategy ensures the swift implementation of post-earthquake repair measures, resulting in reduced direct repair expenses and minimizing the indirect losses associated with downtime.

Code provisions comprehensively address the design considerations for these components (Kappos and Mikes, 2022). American seismic design practices, as exemplified by Caltrans (2019), emphasize the requirement that "*seismic joints must accommodate the necessary horizontal movements and rotations while maintaining full functionality with minimal or no damage under the Functional Evaluation Earthquake (FEE)*." However, these guidelines do not provide specific provisions regarding the size of these joints.

Eurocode 8 Part 2 (EC8-2) (CEN 2004) includes a specific provision for the size ($d_{Ed}$) of ‘expansion’ joints between the deck and the abutments:

$$\mathrm{d_{Ed}} = 0.4\mathrm{d}_E + \mathrm{d}_G + 0.5\mathrm{d}_T \qquad (1)$$

where $d_E$ is the seismic displacement, $d_G$ the displacement from permanent and quasi-permanent actions, including prestressing after losses, shrinkage and creep in concrete bridges, and $d_T$ is the displacement due to thermal movements. The fractions of $d_E$ and $d_T$ are chosen “*based on a judgement of the cost-effectiveness of the measures taken to prevent damage*”. Note that only 40% of the seismic displacement is taken into account, hence closing of the joint is indeed envisaged under the design earthquake. Actually, the Code (correctly) states that this is the case that abutment backwalls can be considered as ‘sacrificial’ elements.

If the designer decides that the abutments should be treated as ‘critical’ elements and their backwalls are no more deemed as ‘sacrificial’, another clearance is specified, namely:

$$\mathrm{d_{Ed}} = \mathrm{d}_E + \mathrm{d}_G + 0.5\mathrm{d}_T \qquad (2)$$

where the full seismic displacement is now taken into account. The same value is also taken to design overlap length between the deck and the abutment seat, as, unseating is a ‘critical’ failure mode. In this context, Kappos (2019) proposed an optimization of the joint gap size in seismic bridge design, proposing a methodology that considers multiple criteria, introduces the concept of a '*Dynamic Intelligent Bridge*' with variable-width joints, and incorporates a novel device, the Moveable Shear Key (MSK), to enhance joint behaviour under seismic loading.

### 2.3 Behaviour and modelling

A typical bridge abutment-backfill system exhibits a complex nonlinear dynamic response when subjected to high seismic actions. The longitudinal motion of the bridge deck can result in a collision between the deck and the abutment backwall, while the reversal of inertial forces may lead to the unseating of the deck from the abutment.

Pioneering analytical studies in the field were conducted by Maragakis *et al.* (1989), focusing on the impact phenomenon between bridge decks and abutments during strong seismic events. They proposed a simplified model to investigate the influence of various parameters, particularly the non-linear behaviour of bridge elements such as foundations and columns, on the bridge deck-abutment impact that occurs after gap closure at abutment joints. The analysis, utilizing this model, was exemplified through the study of a short two-span bridge located in Riverside, California, U.S.

Analytical studies of pounding were carried out using a number of different approaches that can be classified into two main categories:

**(i)** Models based on the *conservation of momentum* principle (also called '*stereomechanical* approach'); this is a rational model based on the relationships

$$v_1' = v_1 - (1+r)\frac{m_2(v_1 - v_2)}{m_1 + m_2} \tag{3a}$$

$$v_2' = v_2 + (1+r)\frac{m_1(v_1 - v_2)}{m_1 + m_2} \tag{3b}$$

where $v_1$ and $v_2$ are the velocities of the colliding bodies, having mass $m_1$ and $m_2$, respectively, the dash denotes that velocities are taken after impact and $r$ is the coefficient of restitution which describes the energy dissipation during impact ($r$=1 for elastic impact, and $r$=0 for fully plastic impact). This approach has been rarely applied to bridges (e.g., DesRoches and Muthukumar, 2002); the main reason for its limited application is that it can only address SDOF systems in contact, rather than realistic configurations with multiple degrees of freedom as those commonly used in finite element analysis.

**(ii)** Models involving *contact elements* (sometimes called '*force-based* approach'), wherein a spring with high stiffness subsequent to gap closure is placed at the (predefined) points of contact, usually coupled with a dashpot to account for energy dissipation. Depending on the way dissipation is modelled, the following models result: linear viscoelastic (Kelvin-Voigt), Hertz, 'Hertzdamp', and the nonlinear viscoelastic model (see reviews in Miari *et al.* (2021) and Jankowski and Mahmoud (2015)). It is worth noting that the main rational way to define the dashpot characteristics in these models is to relate it to the stereo mechanical model, in which case the damping coefficient and the damping ratio are defined as (Anagnostopoulos, 2004):

$$c = 2\xi\sqrt{\left(k\frac{m_1 m_2}{m_1 + m_2}\right)} \tag{4a}$$

$$\xi = -\frac{\ln r}{\sqrt{\pi^2 + (\ln(r))^2}} \tag{4b}$$

In addition to the above '1D' approach involving 'contact elements', 2D and 3D approaches have also been used which can account for additional features such as friction (Shi and Dimitrakopoulos, 2017) and skew angle. Due to their complexity and the fact that they are not amenable to being incorporated in 'standard' finite element programs, the use of such models is restricted to research studies focusing on pounding. It is important to note that the vast majority of the analytical and computational studies on bridge pounding has been limited to pounding between deck segments, which is a well-defined problem, as the masses and stiffnesses of the colliding bodies are known.

On the contrary, in the case of pounding between the deck and the abutment-backfill system, neither the mass nor the stiffness of the latter are well defined. Clearly, considering only the abutment (and indeed the backwall that plays the key role in seat-type abutments) underestimates both the mass and the stiffness of the system. In fact, the definition of the parameters in Eq. (1) and (2) for a colliding body consisting of two different materials, each of which occupies a different portion of the total mass, is an open theoretical problem in Impact Mechanics (Romstad *et al.*, 1995); its solution, even for a specific case, would be a significant step forward and hopefully pave the way for further research in this direction.

In addition to investigating the impact phenomenon, extensive research efforts have been dedicated to assessing the appropriate stiffness and capacity of abutment backfill soil. The lateral load capacity of the abutment backwall entails two key components: one necessary for soil failure along its basal slip surface and another required for sliding the passive wedge of the backfill along the sides of the abutment wingwalls. All the available tests were carried out under static conditions where the static loading consisted of a rigid backwall (assumed to 'shear-off' at an early stage, to act as a fuse for protecting foundation members of a seat-type abutment) applying passive pressures on a backfill soil (sand or clay) (e.g., Romstad *et al.*, 1995; Bozorgzadeh *et al.*, 2008; Lemnitzer *et al.*, 2009). The aforementioned tests have been particularly useful in developing and verifying constitutive relationships for the abutment-backfill system (e.g., Siddharthan *et al.*, 1997; Shamsabadi *et al.*, 2007; Khalili-Tehrani *et al.*, 2016), but offer nothing related to pounding.

Therefore, understanding the behaviour of bridges with seat-type abutments under seismic conditions is vital for ensuring their resilience and reliability in the face of such challenges. In fact, current engineering practices (see also Section 2.2) often neglect or give minimal consideration to the significant impact of nonlinear abutment-backfill soil interaction during dynamic action (i.e., impact) on the seismic behaviour of bridges (Ouanani and Tiliouine, 2017). When exposed to seismic actions, the dynamic response of backfill soil, the inertia and motion of the wall, and their intricate interaction pose considerable challenges for prediction (Wilson, 2009). The nonlinear interaction between abutment and backfill soil during dynamic actions, particularly the impact experienced during seismic events, significantly affects the seismic behaviour of bridges.

Earthquake-induced inertial forces and motions can significantly elevate structural demands, surpassing those under static active or at-rest earth pressure conditions (Kramer, 1996). Additionally, the stability of a retaining wall may be compromised as the resisting passive earth pressure diminishes (Kramer, 1996). Nakamura (2006) also found out that the inertial force was not consistently transmitted to both the wall and backfill simultaneously.

Key areas of uncertainty include the impact of rapid loads on the force-displacement relationship, the influence of damping characteristics, and the determination of participating masses within the backfill. Consequently, there exists a substantial knowledge gap in comprehending the complex dynamics and behaviours associated with nonlinear abutment-backfill soil interaction during seismic events, highlighting the need for further research in this critical area.

# 3 Experimental setup

## 3.1 SoFSI-Soil Pit facility

The University of Bristol established the UKCRIC Soil-Foundation-Structure Interaction Laboratory (SoFSI). The facility is designed to facilitate large-scale prototype experiments, serving both academic and industrial purposes. It addresses critical knowledge gaps that conventional, smaller-scale laboratory tests or prototype observations cannot resolve. The SoFSI Facility offers the unique and high-value capability to test large structural specimens (structural components at a scale as close to prototype as possible) resting on realistic soil conditions within a well-controlled instrumented environment. The SoFSI facility comprises:

- A 6m x 4m biaxial shaking table with a 50-ton capacity, meeting BELLCORE test standards, featuring a peak acceleration of 2g, and a maximum frequency of 50Hz.
- A 6m x 5m test pit with a 4-meter depth, complemented by adjacent strong floors for the installation of two 1MN pseudo-static actuators (with 1000 mm stroke) and one 1MN dynamic actuator (with a 500mm stroke).

- A high-g multi-axis simulation table with a 500kg capacity, capable of reaching a peak acceleration of 8g.

*Figure 3. Photo of the 6m x 5m test pit with a 4-meter depth.*

For the specific tests at hand, the 6m x 5m test pit will be the facility employed, see Figure 3.

### 3.2 Alternative experimental setups

The primary objective of these experiments is to induce an accelerated motion in a mass, simulating the bridge deck, to impact the backwall-backfill system to model pounding in seat-type abutments. This mass is defined to possess a specific kinetic energy ($0.5 \cdot m \cdot v^2$), which is representative of the conditions at the moment of impact.

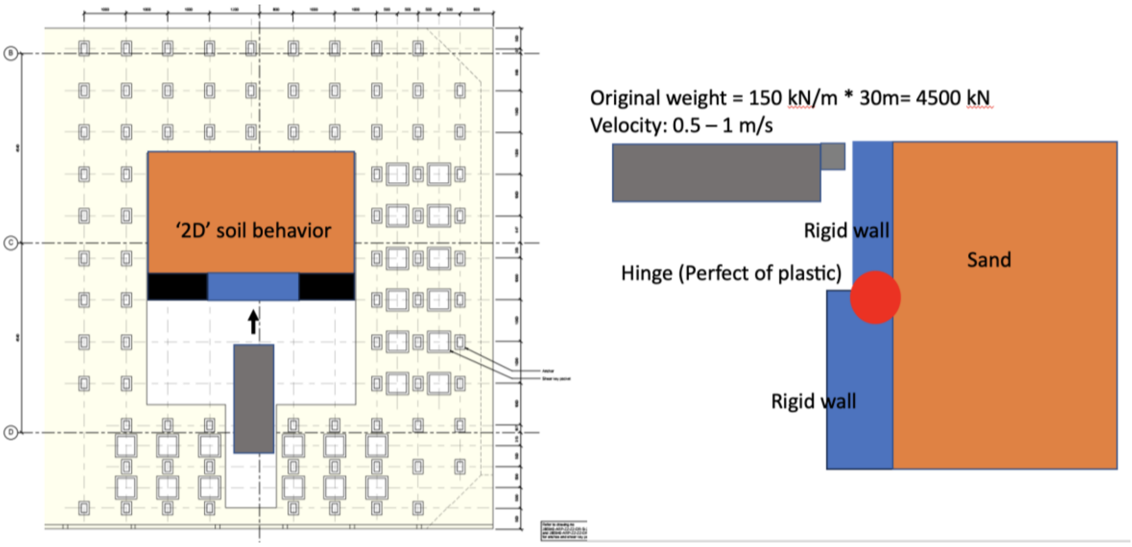

*Figure 4. General overview of the setup: (left) top view of 5m test pit and (right) lateral view.*

The defined mass emulates that of a simply supported deck with a span of 30 meters and is assumed to have a uniform weight of 150 kN/m. To establish the range of velocities at which the mass should make contact, an extensive computational analysis was conducted. Specifically, non-linear dynamic analyses of a symmetric bounded single DoF system were performed, encompassing a comprehensive dataset of 940 distinct time histories, each associated with varying magnitudes and distances. These analyses considered a range of bridge characteristics, including damping ratios falling within the interval of 0.01 to 0.03, periods spanning from 0.2 to 1 second, and expansion gaps measuring between 5 to 20 cm. The results from these calculations have established that the velocity at contact should ideally fall within the range of 0.5 to 1.5 m/s, ensuring a realistic representation of the dynamic impact conditions.

To accommodate the limitations of the facility, a scaling procedure will be executed to downsize both the masses and the specimens, which would otherwise be impractically large. The scaling process will adhere to the following principles:

1. Width of the deck (2D assumption): The scaling will involve a reduction linearly proportional to the width of the bridge deck (i.e., a slice of the bridge deck is assumed). This scaling is based on the 2D assumption of the behaviour of the backwall-backfill system.
2. Kinetic energy equivalence (mass and velocity): The scaling process will ensure that the resulting scaled system possesses kinetic energy equivalent to that of the full-scale structure. By adjusting both the mass and velocity of the scaled components, the impact conditions will remain consistent with the prototype structure.
3. Geometry scaling: The geometry of the specimens will be scaled down while maintaining geometric similarity, thereby preserving the structural characteristics and interactions observed in the full-scale setup. This approach ensures that the scaled-down experiments remain a representative model of the prototype structure.

The application of these scaling principles will enable the successful execution of experiments within the limits of the testing facility.

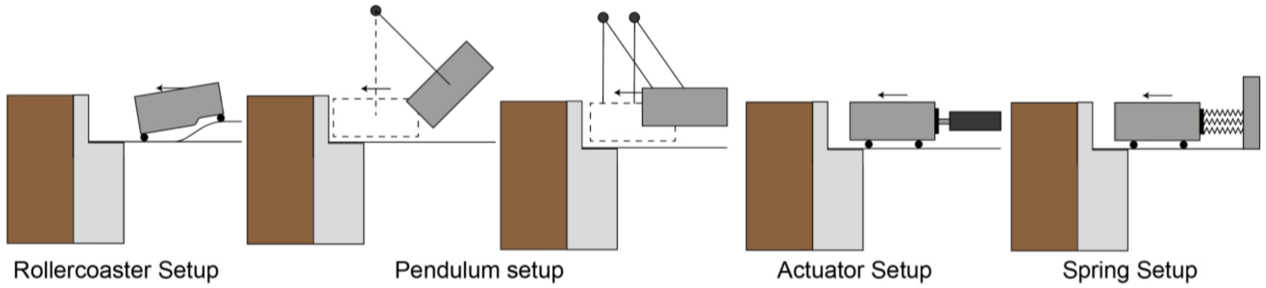

*Figure 5. Schematic of the four possible alternative configurations of the experimental set-up.*

The PoundBack$^2$ research team has devised four alternative experimental setups, each presenting unique features and advantages. These solutions are (see Figure 5): (*i*) ‘Rollercoaster’ setup; (*ii*) Pendulum setup (2 alternatives); (*iii*) Actuator setup; (*iv*) ‘Spring’ setup. The setups invoke different methods to accelerate the mass: gravity in the Rollercoaster setup and Pendulum setup, a hydraulic pump in the Actuator setup, and the kinetic energy stored in a spring in the Spring setup. In the following, we provide brief descriptions of the four setups designed for the PoundBack$^2$ project.The Rollercoaster setup is characterized by the use of gravity as a driving force to propel the mass along a curved track, similar to how a rollercoaster ride operates in an amusement park. The Rollercoaster setup harnesses potential energy by raising a portion of the mass to a certain height, allowing it to descend freely along the track. Specifically, only a couple of the four wheels of the mass are elevated, see Figure 5. The elevation is obtained through a rail system curved. The system is triggered by moving the mass until reaching the downhill part.

The Pendulum setup shares a similar underlying principle with the Rollercoaster setup, based on the conversion of potential energy into kinetic energy. For the Pendulum setup, two distinct configurations were devised: one featuring a single cable and another with dual cables. In the single cable arrangement, the mass is suspended through a cable attached to a frame. The height from which the mass falls is achieved by releasing it from an elevated position, and the swinging motion generates the kinetic energy necessary to simulate the dynamic forces experienced by bridge decks during seismic events. However, in this configuration a challenge arises due to the potential for the mass to rotate and collide perpendicularly with the rear wall's surface. Furthermore, the cable must be attached at or near the center of mass, unless a rigid arm is employed to mitigate this issue. In the two cable configuration, orthogonal collisions are permissible, and there is more flexibility in terms of where the mass can be attached, as it need not be precisely at the center of mass. In both configurations, the use of a rigid arm can greatly assist in managing the pendulum system.

The fundamental principle behind both Rollercoaster and Pendulum setups is the conversion of potential energy into kinetic energy, replicating the dynamic forces encountered by bridges during seismic events. The height required for the Rollercoaster setup can be calculated using the Torricelli equation, $h = \sqrt{v^2/2g}$ where $h$ is the required height, $v$ is the required velocity and $g$ is the gravity acceleration. To achieve a velocity of 1-1.5 m/s, an approximate height of around 10-15 cm is determined (neglecting energy dissipation effects). In the Actuator setup, a dynamic servo-hydraulic actuator is employed to accelerate the mass positioned on a rail. Once the desired velocity is achieved, a detach system separates the mass from the actuator, allowing it to continue its movement (along a rail system) independently and reach the intended impact point. This setup utilizes advanced servo-hydraulic technology to accurately control and release the mass.The Spring setup involves an initial movement of the mass to load a spring system situated on the rear side. During this process, elastic energy is gradually stored within the springs (which can have alternative forms, e.g., consists of thin metal plates). Subsequently, a sudden release mechanism is activated, converting the accumulated elastic energy into kinetic energy.

In each of these setups, a dedicated system has been incorporated to prevent the mass from experiencing multiple impacts during the rebound phase. This feature is essential for ensuring the effectively stopping the mass after the initial impact. As of the time of writing this paper, the Rollercoaster setup stands as the most favourable choice among these alternatives.

### 3.3 Specimens and test matrix

The specimen should be as realistic as possible (a key novelty of PoundBack$^2$ is that it will entail damage in both the structure and the soil), but also feasible. Moreover, it should allow to carry out the different tests envisaged (see below). Therefore:

- The specimen should consist of two ‘blocks’, an upper, thinner, one representing the backwall of a seat-type abutment and a thicker one representing the stemwall (see Figure 6). At least the backwall should be as close to a realistic reinforced concrete (RC) member as possible, but it should also allow disconnecting it from the stemwall in an easy way. Hence, in lieu of conventional reinforcement consisting of steel bars continuing into both ‘blocks’ and anchored in the normal way, lightly prestressed bars with threading at the end can be used, which are continued into the stemwall and are anchored there in threaded grooves (not shown in Figure 6); in this way proper anchorage can be achieved, but also it is possible to remove the bars by unthreading them and separate the two blocks.
- The base of the backwall will be designed having the bridge prototype in mind and will correspond to the most common in Southern Europe and many other areas ‘hinging’ backwall, i.e., a wall that will yield during the design seismic action and will subsequently rotate, basically as a rigid member, as shown in previous studies, e.g., Mikes and Kappos (2021, 2023). Test protocols will be designed in such a way that the abutment specimen will remain (essentially) elastic in the first series of tests, and the backwall (the top block) will yield and deform inelastically in subsequent tests (see test matrix).
- The ‘shearing off’ backwall of Caltrans is easy to model by completely disengaging the two blocks and applying the loading at the backwall block (same setup, but the stemwall block will just support the upper block).
- The aforementioned (and other) studies have shown that the displacements of the stemwall are significantly smaller than those of the (more flexible and also hinging) backwall. Nonetheless, since the foundation of the abutment will not be directly simulated in the specimen, the base of the backwall should be properly restrained against both rotation and horizontal displacement, but not fixed (it is not feasible to fix it in the lab, as the floor around the pit is not a strong floor). This can be achieved by placing the base of the bottom block in a groove (see Figure 6), possibly lined with elastomeric material, and calibrate its rotation and displacement to be the same as those at the same location of a full model of the abutment and its foundation.

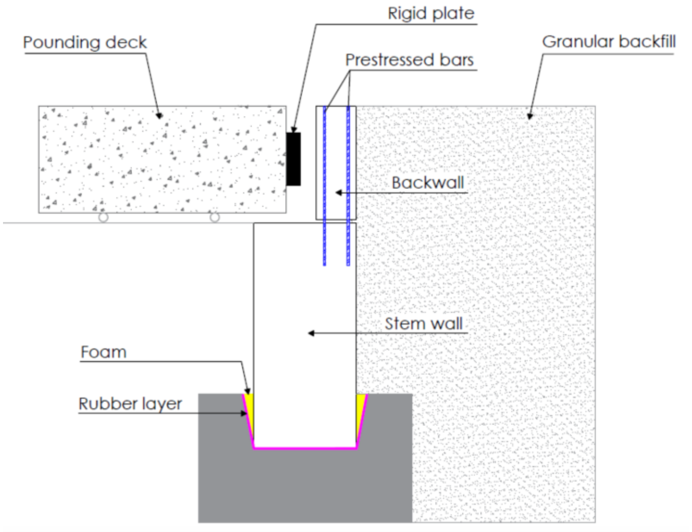

*Figure 6. Detail of the setup of the wall system.*

From a design point of view, the Ultimate Limit State is important and leading codes like Caltrans (2019) assume just nominal strength of the backwall, which is supposed to 'shear off' during the design earthquake and deflect horizontally without any rotation. This was the unrealistic but convenient 'scenario' assumed in the well-known experiments (static pushover type) on abutment backfill systems, referred to in Section 2.3.

However, for research purposes, all phases of the abutment-backfill response are interesting and offer the possibility to compare parameters like the participating mass of the backfill and the coefficient of restitution for different cases. Therefore, the following schedule of tests is envisaged:

- ***Case 1***: The abutment remains in the (quasi-)elastic range and is 'stand-alone' (no backfill). This a useful starting point, especially in the context of calibrating the effective masses during pounding, but also offering the possibility of comparing with past tests (e.g., Saiidi *et al.*, 2013) involving pounding of decks on stand-alone abutments. Of course, in this case one should make sure that there is sufficient rotational resistance at the bottom of the stemwall.
- ***Case 2***: Backfill soil is added and everything remains in the (quasi-)elastic range; of course, the velocity pulses to be applied should be low enough to avoid damage in either the abutment or the backfill. An accurate estimation of the yield strength of the backwall is critical in this respect.
- ***Case 3***: This is the 'hinging' abutment case; setup is as in Case 2 but higher velocities are applied, leading to damage in both the abutment and the backfill soil. Interpretation of results is more difficult in this case, but this is clearly the heart of the project, an SSI test that has never been carried out before.
- ***Case 4***: This is the 'shearing-off' abutment case; it involves two important changes in the set-up (i) the two blocks are separated (by unscrewing the threaded bars connecting them), so the backwall is just standing on the stem wall (simulation of complete shearing off) (ii) the upper part of the backfill, down to a few centimetres below the backwall base is replaced and reconstructed, to be practically the same as in the pristine specimen (Cases 1 and 2). Depending on the damage incurred in Case 3, a pristine backwall block may be needed in this case. The displacement profile of the backwall is now significantly different than in Case 3 and it remains to see how much difference this will make in the pounding parameters.

## 4 Expected results

The ERIES-PoundBac$^2$ project promises to yield insights and invaluable data that have never been explored before. The primary novelty of the project is the pioneering experiment focusing on pounding within the abutment-backfill system at nearly full scale, a domain that has remained largely uncharted in previous studies. The anticipated impact of this project is substantial and multifaceted. Beyond merely addressing the pounding effects within bridge structures, it promises to provide comprehensive insights into the dynamic behaviour of abutment-backfill systems during seismic loading. While past studies have predominantly focused on the soil component and recorded damage in the soil rather than the structure, this project intends to bridge this gap. It will shed light on the complex interaction between backfill and abutment under dynamic loading conditions, unravelling unexplored aspects of seismic response in this context. Furthermore, the large-scale tests will serve as a pivotal validation platform for advanced models designed for bridges with seat-type abutments. This, in turn, will significantly contribute to advancing research in the field and potentially influence the development of seismic code provisions, including the forthcoming new Eurocode 8 Part 2.

## 5 Concluding remarks and future perspectives

The ERIES-PoundBac[2] project represents a pivotal advancement in the field of bridge engineering. By addressing the critical gap in our understanding of bridge pounding during seismic events, especially in bridges with seat-type abutments, this project is poised to deliver invaluable insights into bridge behaviour and performance. The comprehensive experiments planned for 2024, hosted at the state-of-the-art SoFSI-Soil Pit facility at the University of Bristol, are expected to provide a wealth of experimental data and knowledge. This research promises to be a stepping stone for future studies and advancements in understanding the nonlinear abutment-backfill soil interaction under dynamic actions, ultimately contributing to safer and more resilient bridge structures globally.

As this is an ongoing project, results will be available in the new future (Spring 2024) and the final presentation at the WCEE is expected to include much more detail than the present paper.

## Acknowledgements

This work is part of the transnational access project “ERIES – PoundBac[1]”, supported by the Engineering Research Infrastructures for European Synergies (ERIES) project (www.eries.eu), which has received funding from the European Union’s Horizon Europe Framework Programme under Grant Agreement No. 101058684. This is ERIES publication number C12.

## References

Anagnostopoulos SA (2004) Equivalent viscous damping for modeling inelastic impacts in earthquake pounding problems. *Earthq. Engng Struct Dynamics*; **33**:897–902.

Bozorgzadeh A, Ashford SA, Restrepo JI (2008) Effect of backfill soil type on stiffness and capacity of bridge abutments. Proceed. 14th WCEE, Beijing; paper 04-02-0047.

Caltrans (California Department of Transportation) (2019). Seismic Design Criteria (version 2.0). Oakland, CA, USA.

CEN (Comité Européen de Normalisation) (2012). Eurocode 8: Design of structures for earthquake resistance - Part 2: Bridges (EN 1998–2:2005 + A2:2011), Brussels.

DesRoches R, Muthukumar S (2002) Effect of Pounding and Restrainers on Seismic Response of Multiple-Frame Bridges *J Struct Engng, ASCE*; **128**(7): 860-869.

DesRoches R, Muthukumar S (2004) Implications of seismic pounding on the longitudinal response of multi-span bridges – an analytical perspective. *Earthq Engng & Eng Vibr*; **3**:57–65.

Fiorentino, G., Cengiz, C., De Luca, F., Mylonakis, G., Karamitros, D., Dietz, M., Dihoru, L., Lavorato, D., Briseghella, B., Isakovic, T., Vrettos, C., Topa Gomes, A., Sextos, A. G., & Nuti, C. (2021) Integral abutment bridges: Investigation of seismic soil - structure interaction effects by shaking table testing. Earthquake Engineering & Structural Dynamics, V. 50, no. 6: 1517-1538.

Guo A, Cui L, Li S, Li H (2015) A phenomenological contact element model considering slight non-uniform contact for pounding analysis of highway bridges under seismic excitations. *Earthq. Engng & Struct Dynamics*; 44:1677–1695.

Jankowski R, & Mahmoud S (2015) *Earthquake-Induced Structural Pounding*, Springer.

Kappos, A.J. (2019) The dynamic intelligent bridge: A new concept in bridge dynamics, Ch. 28 in Rupakhety et al. (eds.), *Proceedings of the International Conference on Earthquake Engineering and Structural Dynamics*, Springer; 373–383.

Kappos, A. J., & Mikes, I. (2022). Optimum Design of Seismic Joints in Bridges. In *European Conference on Earthquake Engineering and Seismology* (pp. 323-342). Springer International Publishing.

Khalili-Tehrani, P., Shamsabadi, A., Stewart, J.P. & Taciroglu, E. (2016) Backbone curves with physical parameters for passive lateral response of homogeneous abutment backfills. *Bull. of Earthq. Engineering*; **14**(11):3003–3023.

Kramer, S. (1996). *Geotechnical Earthquake Engineering*. Prentice Hall, Upper Saddle New Jersey.

Kun C, Jiang L, Chouw N (2017) Influence of pounding and skew angle on seismic response of bridges. *Engng Struct*; **148**:890–906.

Lemnitzer A, *et al.* (2009) Lateral Performance of Full-Scale Bridge Abutment Wall with Granular Backfill. *J Geot & Geoenv Engng, ASCE*; 135(4); 506-514.

Maroney, B.H, (1995) Large Scale Abutment Tests to Determine Stiffness and Ultimate Strength Under Seismic Loading, Ph.D. Dissertation, University of California, Davis.

Miari, M., Choong, K. K., & Jankowski, R. (2021). Seismic pounding between bridge segments: a state-of-the-art review. *Archives of Computational Methods in Engineering*, ***28***, 495-504.

Mikes IG, Kappos AJ (2021) Simple and complex modelling of seat-type abutment-backfill systems. Proceed. COMPDYN 2021, Athens; Vol. 2, 5266-5282.

Mikes, I.G. and Kappos, A.J., (2023). “Optimization of dynamic response of bridges with variable- width joints”. Earthquake Engineering & Structural Dynamics, V. 52, no. 1: 111- 127.

Mylonakis, G., Gazetas, G. (2000) Seismic soil-structure interaction: beneficial or detrimental? Journal of Earthquake Engineering, V. 4, no. 3: 277–301.

Nakamura (2006). “Reexamination of Mononobe-Okabe theory of gravity retaining walls using centrifuge model tests.” *Soils and Foundations,* The Japanese Geotechnical Society, Vol. 46, No. 2, 135-146.

Ouanani, M., & Tiliouine, B. (2017). Progressive seismic failure of a highway bridge, including abutement–backfill interaction. *Current science*, 355-363.

Romstad K *et al.* (1995) Experimental measurements of bridge abutment behavior; Report No. UCD-STR-95-1, UC Davis.

Saiidi, MS, Vosooghi A, Ashkan M Nelson RB (2013) Shake-Table Studies of a Four-Span Reinforced Concrete Bridge, *J Struct Engng, ASCE*; **139**(8): 1352-1361.

Shamsabadi A, Rollins KM & Kapuskar M (2007) Nonlinear soil–abutment–bridge structure interaction for seismic performance-based design. *J Geot & Geoenv Engng, ASCE*. **133**(6): 707–720.

Shamsabadi, A., Khalili-Tehrani, P., Stewart, J. P., & Taciroglu, E. (2010). Validated simulation models for lateral response of bridge abutments with typical backfills. *Journal of Bridge Engineering*, *15*(3), 302-311.

Shi Z, Dimitrakopoulos EG (2017) Nonsmooth dynamics prediction of measured bridge response involving deck-abutment pounding. *Earthq. Engng Struct Dynamics*; **46**:1431–1452.

Sidarthan, R.V., El-Gamal, M., Maragakis, E.A., (1997). “Stiffnesses of abutments on spread footings with cohesionless backfill.” Canadian Geotechnical Journal; 34: 686–697.

Taskari, O., Sextos, A.G. (2015) Probabilistic Assessment of Abutment-Embankment Stiffness and Implications in the Predicted Performance of Short Bridges. Journal of Earthquake Engineering, V. 19, no. 5: 822–846.

Wieser, J., Zaghi, A. E., Maragakis, M., & Buckle, I. (2012). A methodology for the experimental evaluation of seismic pounding at seat-type abutments of horizontally curved bridges. In *Structures Congress 2012* (pp. 613-624).

Wilson, P. R. (2009). *Large scale passive force-displacement and dynamic earth pressure experiments and simulations*. University of California, San Diego.

Zheng, Q., Yang, C. S. W., Xie, Y., Padgett, J., DesRoches, R., & Roblee, C. (2021). Influence of abutment straight backwall fracture on the seismic response of bridges. *Earthquake Engineering & Structural Dynamics*, *50*(7), 1824-1844.

Zhu P, Abe M, Fujino Y (2002) Modelling three-dimensional non-linear seismic performance of elevated bridges with emphasis on pounding of girders. *Earthq. Engng & Struct Dynamics*; **31**:1891–1913.