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Centrifuge modelling of the dynamic behavior of an old masonry wall in sand

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ABSTRACT: This study investigates the seismic behavior of shallow foundations in historic masonry buildings through centrifuge modelling. Two centrifuge tests were performed: one under saturated conditions with low excess pore pressure, and another under dry conditions to assess the impact of increased pore pressure on structural response. In the dry condition test, two similar structures were compared, one with foundation connections, the other lacking them. Instrumentation during the experiments measured deformation, rotation and settlements, pore water pressures, and stress distributions within the soil and the masonry walls. The findings emphasize that the presence of a water table alters stress distribution and foundation performance under dynamic loading. Additionally, enhanced masonry joint connectivity was demonstrated to markedly improve structural integrity by more effectively distributing seismic loads across the foundation. Additionally, air hammer tests and Particle Image Velocimetry (PIV) analysis were performed to further investigate soil-structure interaction and dynamic response. The results offer valuable insights for the preservation and seismic retrofitting of historical buildings, at low rate of excess pore water pressure, enhancing the understanding of complex behaviours under seismic loading.

1 INTRODUCTION

Small-scale physical modelling, and centrifuge modelling in particular, plays a crucial role in geotechnical engineering research. It enables the realistic simulation of stress-dependent soil behaviour, and a systematic control of material properties and boundary conditions. By subjecting a scaled model to an increased gravitational field, the stress state of the prototype is replicated, ensuring realistic strength, stiffness, and deformation mechanisms. Even if models do not perfectly mirror prototype complexities, this approach is indispensable for validating constitutive and numerical models and for investigating scenarios, like seismic shaking, that are impractical or impossible to reproduce at full scale (Schofield 1980, Gaudio et al 2024a and 2024b).

This proceeding presents experimental results from two centrifuge tests carried out within the framework of the GIANO (Geo-Risks Assessment and Mitigation for the Protection of Cultural Heritage) research project, which focuses on geotechnical hazards to historic structures. The work specifically investigates the seismic vulnerability of shallow-founded historic masonry buildings through centrifuge tests conducted at the Schofield Centre, University of Cambridge. The experimental campaign comprised two tests, performed on the same stratigraphy:

- GIANO-1 under saturated conditions with a single masonry structure on sand
- GIANO-2 under dry conditions comparing two identical structures—one connected by a wooden slab foundation link, the other unconnected.

This setup is designed to isolate the influence of the different factors: low-moderate excess pore pressure ratio buildup under shaking, water table effects, and foundation connectivity impacts on settlements and rotations. Results support seismic retrofitting strategies for historic shallow-founded masonry, emphasizing joint enhancements for load distribution.

2 TESTING PROGRAM

The experimental campaign was carried out at the Schofield Centre, University of Cambridge, using the Turner beam centrifuge. This facility can achieve accelerations up to 150g and is equipped with a servo-hydraulic actuator capable of applying realistic dynamic seismic loading.

A centrifugal acceleration of 60g was selected for the modelling phase to ensure an adequate representation of the prototype stress conditions.

2.1 Soil Model and Stratigraphy

The model was housed in a rigid box with internal dimensions of 730 mm (length) × 250 mm (width) × 370 mm (height). To mitigate boundary effects, the container sidewalls were lined with 25 mm-thick layers of Duxseal, a damping material that significantly reduces seismic wave reflections (Steedman and Madabhushi, 1991).

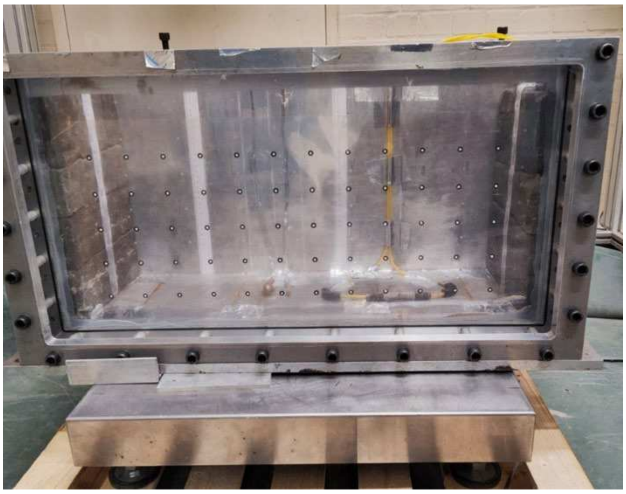

Figure 1 Rigid box with perspex window

A transparent 80 mml-thick Perspex window allowed in-flight deformation monitoring by means of Particle Image Velocimetry (PIV). For dynamic soil characterization, an air hammer was installed at the base of the model to generate controlled shear waves, from which shear-wave velocity profiles were derived using arrays of piezoelectric accelerometers.

The soil used in these tests is Hostun Sand (HN31), a well-characterized silica sand with colors ranging from white-grey to pink-beige and grain shapes from angular to sub-angular. Hostun Sand has been extensively studied over the past 30 years, with specific gravity $G_s = 2.65$, maximum and minimum void ratio $e_{max} = 1.05$ and $e_{min} = 0.65$, and critical state friction angle $\varphi_{cv} = 33°$ (from Kassas et al. 2021 & Kassas et al 2020). To achieve the target relative density Dr0, and guarantee its uniformity in the model, two layers of sand were created using an automatic sand pourer (Madabhushi et al. 2006). A fully automated sand pourer was used to create a uniform, two-layer stratigraphy representative of a crust-over-liquefiable-layer profile ashown in Figure 4 for GIANO-1 test:

- an upper dense crust with a relative density of Dr ≈ 90%.
- an underlying loose layer with a target relative density of Dr ≈ 50%.

To facilitate PIV analysis, approximately one-third of the sand was dyed black.
Two distinct test configurations were prepared:

- GIANO-1 (saturated): the model was saturated with a methylcellulose pore fluid to satisfy viscosity-based scaling laws. The water table was positioned at a prototype depth of 2.0 m, leaving the dense crust above the phreatic surface and the loose layer fully saturated with a final Dr ≈ 55%
- GIANO-2 (dry): the same two-layer stratigraphy was reproduced but kept entirely dry. The less handling of the box during preparation resulted in a slightly lower relative density in the loose layer (Dr ≈ 51%) compared to GIANO-1.

2.2 Model structure

The superstructure for the centrifuge tests consisted of a scaled masonry wall designed to represent a heritage building on shallow strip footings while maintaining geometric simplicity for mechanical characterization.

The two configurations tested were:

- For GIANO-1 (saturated): a structure comprising two parallel masonry walls interconnected by two rows of bolted ties.
- For GIANO-2 (dry): two nominally identical structures were tested, one identical to the GIANO-1 configuration and a second variant with a foundation-level connections.

The walls were constructed from fired clay bricks miniature bricks (11 × 6 × 2.5 mm) laid in a single-brick Gothic bond pattern using a cement-based mortar (W/C = 0.72). This bond ensures stability through strong vertical interlocking. The overall structure is 100 mm high on a model scale, corresponding to 6 m at prototype scale. The walls were founded on embedded masonry piers that extended into the soil, forming the strip foundations.

This foundation was embedded at a depth of 1.2 m in prototype scale, coinciding with a foundation width, B, also of 1.2 m, mirroring the typical beam enlargement often adopted for masonry walls.

The entire setup was designed to induce a predominantly two-dimensional, in-plane response, facilitating analysis within a plane-strain framework.

Unconfined compression tests on masonry panels yielded a characteristic strength of approximately 5 MPa, confirming the model's representativeness for historic masonry materials.

Figure 2 Side view of the GIANO-1 test structure before the installation in the centrifuge box.

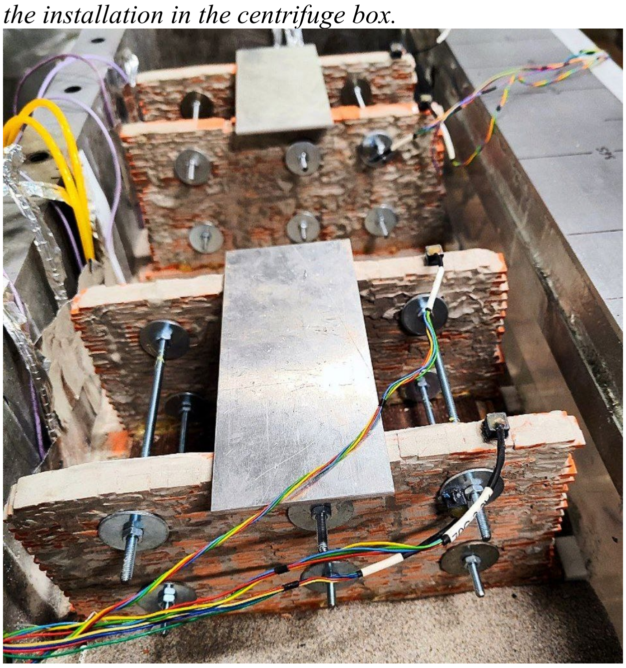

Figure 3 The two structures installed and instrumented in the GIANO 2 test, the plates are used to provide a bearing surface for the LVDTs.

The total applied load, including the weight of the foundations, results in an average footing pressure of about 89 kPa at prototype scale.

Table 1 Geometric dimensions of the GIANO masonry superstructure at prototype scale

PROTOTYPE SCALE	Value	Units
Foundation height	1.2	m
Wall height	6	m
Foundation width	1.08	m
Wall thickness	0.72	m

2.3 Instrumentation and measurements

GIANO tests were comprehensively instrumented to capture soil response, excess pore pressures, structural deformations, and dynamic soil-structure interaction (SSI) under seismic loading.

Instrumentation included accelerometers for ground (PIEZO) and structural motions (MEMS), pore pressure transducers (PPTs) in GIANO-1 for excess pore pressure (Δu) estimation, linear variable differential transducers (LVDTs) for settlements and rotations, high-speed imaging for Particle Image Velocimetry (PIV), which is still in processing, and an air hammer for small-strain soil profiling. Positions of the instruments for GIANO-1 are shown in Figure 4. Midspan cross-section of the box showing instrumentation layout and the relative legend for GIANO-1 test.and followed standard practices: sensors clustered under/around foundations for localized effects, with arrays for wave propagation.

An air hammer at the box base generated low-amplitude shear waves for stiffness profiling. Vertical piezo arrays are aligned along a “free field” vertical and measured the shear wave velocity, yielding small strain stiffens pre- and post-earthquake to characterize the dynamic stiffening/ softening.

2.4 Seismic input

The seismic loading sequence adopted in the GIANO tests is summarized in Table 2 for GIANO-1 test and in Table 3 for GIANO-2 test. After the first sine sweep, four sinusoidal signals and one real earthquake (Tolmezzo) were applied to the model.

The focus will be on Eq5 signal for GIANO-1 and for Eq4 for GIANO-2, a sinusoidal signal with 10 cycles at 1Hz, resulting both in a maximum amplitude (a_{max}) of 0.18g in prototype scale.

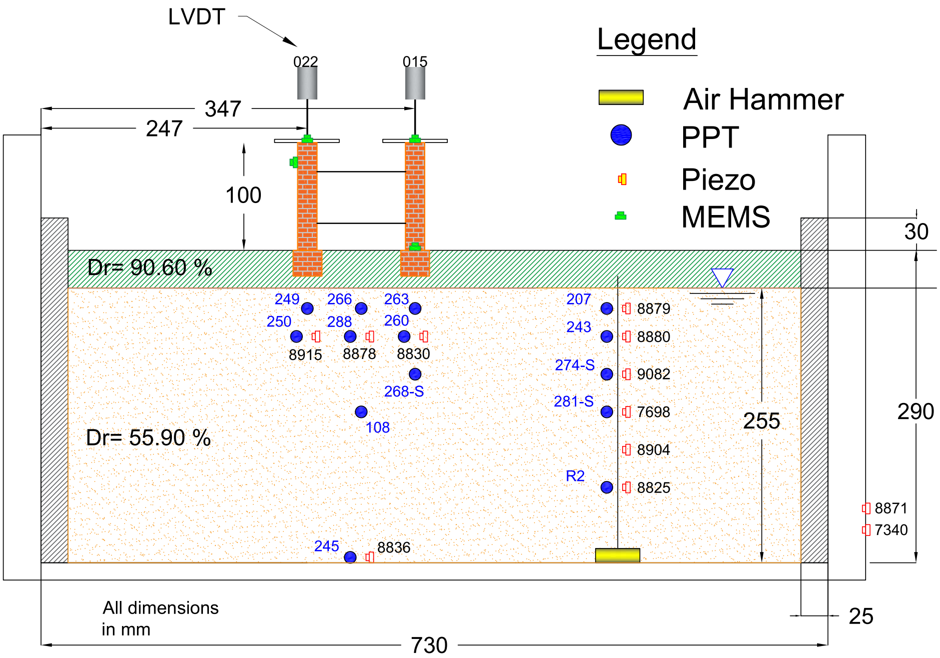

Figure 4. Midspan cross-section of the box showing instrumentation layout and the relative legend for GIANO-1 test.

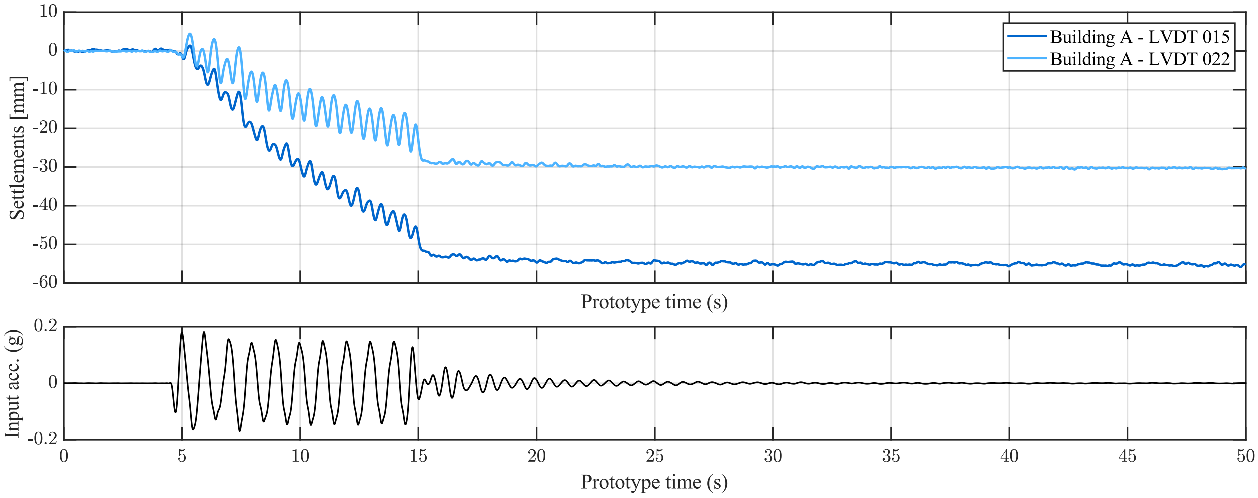

Figure 5 Prototype-scale settlements for GIANO-1 Building A in Earthquake 5 (0.18 g) and corresponding input base acceleration time history

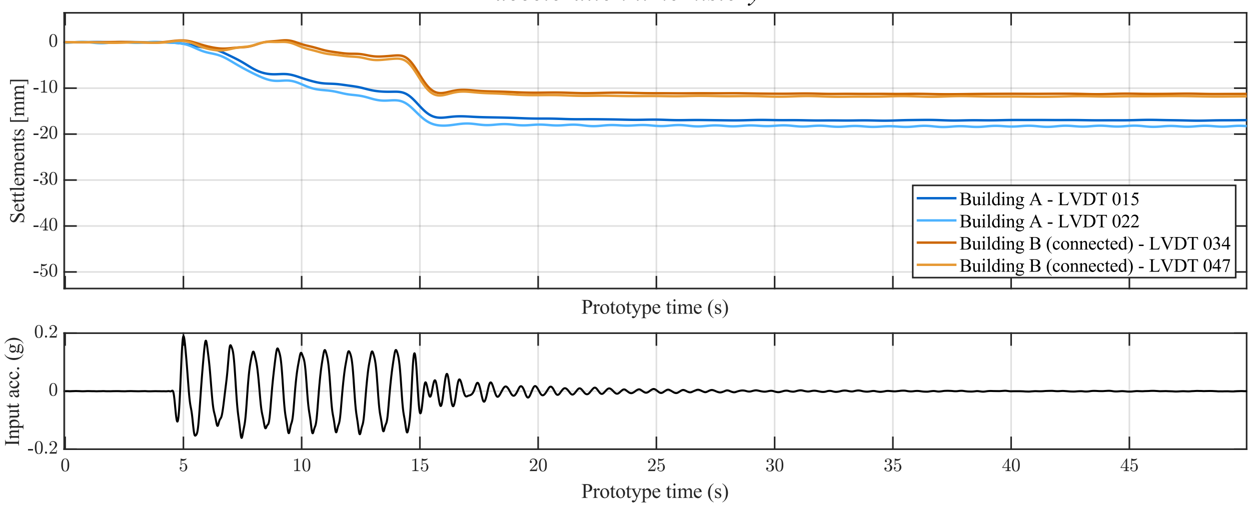

Figure 6 Prototype-scale settlements of Buildings A and B during Earthquake 4 (0.18 g) in GIANO-2 test and corresponding input base acceleration time history.

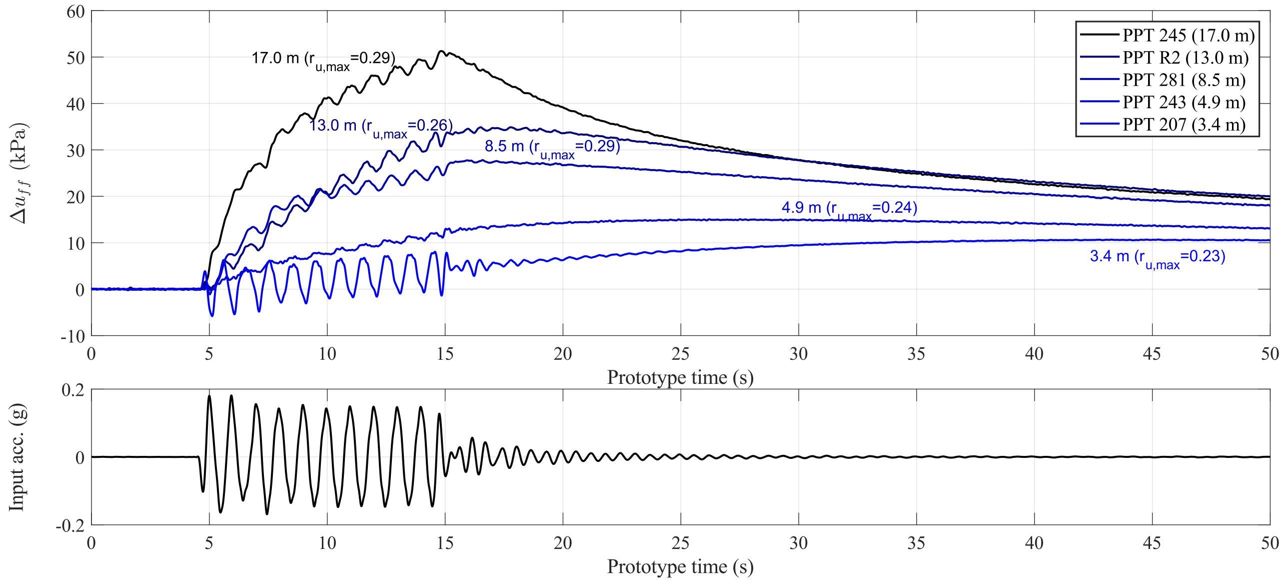

Figure 7 Processed excess pore water pressure in GIANO-1 test for earthquake 5 with their relative depth (prototype scale) along the free field alignment

Table 2 Summary of the seismic loading sequence applied in the GIANO-1 centrifuge test, a_g is the peak acceleration measured at the base of the box.

Phase	Input Signal	a_g
EQ1	Sine sweep	0.02
EQ2 (test)	60Hz,10 cyc, 0.5V	0.02
EQ3	60Hz,10 cyc, 1V	0.08
EQ4	60Hz,10 cyc, 1.5V	0.14
EQ5	60Hz,10 cyc, 2V	0.18
EQ6	Tolmezzo 2V	0.12

Table 3 Summary of the seismic loading sequence applied in the GIANO-2 centrifuge test.

Phase	Input Signal	a_g
EQ1	Sine sweep	0.02
EQ2	60Hz,10 cyc, 1V	0.08
EQ3	60Hz,10 cyc, 1.5V	0.14
EQ4	60Hz,10 cyc, 2V	0.18
EQ5	Tolmezzo 2V	0.12
EQ6	90Hz, 10cyc, 1 V	0.25

3 EXPERIMENTAL RESULTS

All signal outputs from the instruments like accelerometers, LVDTs, and pore pressure transducers, were systematically processed.

Raw signals underwent careful filtering to eliminate noise, delivering stable and reliable time histories for the seismic events and for the static phase of swing up. The data were post-processed in the time and frequency domains, allowing the extraction of key response parameters from acceleration, displacement, and pore pressure records.

For brevity, the results presented here focus on the elaboration of the settlements for GIANO-1 in Eq5 (0.18g), Figure 5, and for GIANO-2 in Eq4 (0.18g), Figure 6, and the excess pore water pressure (Δu_{ff}) shown in Figure 7, as these are most relevant for evaluating the performance of the model configurations.

3.1 Excess pore water pressure

Excess pore water pressure was measured at multiple depths below the foundation and in free field condition; the signals were filtered and averaged over characteristic shaking windows to capture peak and residual responses, as shown in Figure 7. These values were then normalized with respect to initial effective stresses to obtain the excess pore pressure ratios (r_u).

Δu exhibits a clear decreasing trend with depth, while r_u value remain more or less costant ranging from approximately 0.31 down to 0.25.

3.2 Settlements

The time histories of foundation settlement presented in Figure 5 and Figure 6 offer a direct quantitative comparison of the seismic performance observed in the GIANO test series. The data illustrates the influence of soil saturation and foundation connectivity on the dynamic response. For the saturated test GIANO-1 (Building A), the recorded settlements are significantly larger, with a maximum value observed on structure's right wall (corresponding to the left side from the frontal perspective) of 55mm and a differential settlement which is almost half of the total. This occurred despite the soil having a slightly higher relative density compared to the dry test. This counterintuitive result underscores a key finding: even moderate excess pore-pressure ratios (r_u ~ 0.2–0.3 highlighted in Figure 7), well below liquefaction triggering, can generate a loss of soil stiffness and strength, leading to increased cumulative settlements under seismic loading.

In the dry test GIANO-2 Building B demonstrates the efficacy of enhanced foundation connectivity. The connected structure exhibited drastically reduced final settlements (approximately 10 mm). Furthermore, the settlement profiles for the connected foundation show significantly smaller differential settlements between measurement points, indicating a more coherent, box-like response that effectively distributes inertial forces and mitigates damaging rotations.

The presence of a water table poses a critical risk to historic masonry structures even during seismic events of moderate intensity; and secondly, that retrofitting strategies aimed at improving foundation-level connectivity can provide substantial resilience by reducing both total and differential displacements.

4 CONCLUSIONS

The centrifuge test results from the GIANO experimental campaign can provide useful insights into the seismic vulnerability of shallow-founded historic masonry buildings and potential retrofitting strategies. A significant finding is that even modest excess pore-pressure ratios, levels typically considered insufficient to trigger liquefaction and well below codes verification thresholds, can induce a loss of soil stiffness which can lead to rigid body damage, a risk for heritage buildings in saturated conditions, even during seismic events not intense enough to cause liquefaction.

As expected, the experiments clearly demonstrate the effectiveness of improving foundation-level connectivity as a retrofit measure. The structure with interconnected foundations in GIANO-2 exhibited a reduction in final settlement of approximately half compared to the building A, along with drastically reduced rotations and differential settlements.

This experimental evidence also suggests that further investigation is needed to fully understand failure mechanisms; for instance, the rupture observed in the GIANO-2 structure, potentially due to higher seismic demand or specific interaction effects, warrants detailed analysis through techniques like Particle Image Velocimetry (PIV).

The data generated offers a valuable benchmark for validating numerical models and constitutes a solid foundation for further research into the performance and protection of historic masonry structures.

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