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A hybrid c-frame laminar model container with PIV window for dynamic centrifuge testing

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ABSTRACT: Dynamic centrifuge modelling has been recognised as an effective technique for investigating complex seismically-induced geotechnical hazards. Conventional centrifuge containers, such as the laminar box and the rigid Perspex window container, all present limitations—either restricting the ability to capture real-time soil–structure deformations using digital imaging techniques (DIC) or inducing undesirable boundary effects. This paper introduces the design principles of a newly developed hybrid C-frame laminar–window container at the Schofield Centre, University of Cambridge. The new container combines the compliant boundary condition of a laminar box, in the form of C-frames, with the optical accessibility of a Perspex window rigid strong box, enabling direct observation of soil deformation mechanisms using Particle Image Velocimetry (PIV). The performance of the container is demonstrated through two dynamic centrifuge tests, at an inclination of three and six degrees, which confirm both the effectiveness of the flexible boundary condition and the feasibility of this design as a next-generation centrifuge modelling tool.

1 INTRODUCTION

Geotechnical centrifuge modelling has been widely recognised as an effective tool for investigating seismic-related soil–structure interaction problems, as it enables realistic replication of in-situ stress–strain behaviour in scaled models. One of the main challenges in dynamic centrifuge testing, however, lies in mitigating boundary effects introduced by the artificial constraints of model containers. To address this issue, Hushmand et al. (1988) developed the laminar box for liquefaction studies, in which the container walls are composed of stacked frames with low interlayer friction, allowing the soil to deform more freely and experience uniform horizontal acceleration across the boundaries. Similarly, Zeng and Schofield (1996) introduced the equivalent shear beam (ESB) container, featuring flexible frictional end walls formed by aluminium frames separated by rubber layers of varying thickness. This configuration reproduces the progressive increase in soil stiffness with depth and significantly reduces boundary effects. Their experimental results demonstrated reliable wall deformation, a uniform acceleration field, and negligible container rocking. Variants of this container type have since been widely adopted at the University of Cambridge for dynamic geotechnical research (e.g. Chian et al., 2014; Gaudio et al., 2024; Español-Espinel et al., 2025), as well as in other centrifuge facilities worldwide, including the flexible shear beam (FSB) container at UC Davis (Campbell et al., 1991), and ESB containers developed at Tongji University (Cao and Huang, 2010) and KAIST, South Korea (Lee et al., 2013).

With the rapid advancement of particle image velocimetry (PIV) techniques (Adrian, 1991; Stanier et al., 2016), also referred to as digital image correlation (DIC) (Bruck et al., 1989), direct measurement of soil deformations has become an integral part of experimental geotechnics. Over the past two decades, PIV has been widely adopted in centrifuge modelling to capture soil kinematics and failure mechanisms (White et al., 2001, 2003; Stanier and White, 2013; Take, 2015). To facilitate optical access, many centrifuge facilities employ rigid-walled containers fitted with Perspex observation windows (Zhang et al., 2005a, b; He and Madabhushi, 2024). However, the use of rigid side boundaries inevitably introduces significant wave reflection and boundary constraints. Although the installation of deformable Duxseal layers along the container walls can reduce boundary wave reflections by approximately 65% (Steedman and Madabhushi, 1991), these effects cannot be fully eliminated. Ghayoomi et al. (2013) presented a transparent ESB model box, though the limitations of this, particularly in the thickness, and thus the lateral stiffness of the resulting container are discussed in detail in Haigh and Madabhushi (2014). This limitation highlights the need for a new generation of centrifuge containers that combines the compliant boundary behaviour of laminar systems with the optical accessibility of rigid Perspex-windowed boxes, enabling accurate simulation of seismic soil–structure interaction while allowing direct observation of deformation mechanisms using PIV.

2 MODEL CONTAINER DESIGN

The new centrifuge model container was developed based on an existing rigid Perspex model container at the Schofield Centre, University of Cambridge. A series of C-frames was fabricated by cutting one side of a conventional laminar rectangular ring made from an H-section aluminium profile, with PTFE plates inserted into the resulting gaps (similar to the design of Chian et al., (2018)). The PTFE inserts were intentionally made slightly longer than the aluminium sections to minimise side friction against the Perspex wall and to prevent surface damage caused by direct aluminium-Perspex contact.

Prior to sand deposition, the C-frames were assembled inside the rigid Perspex container, with the bottom frame restrained by two rigid aluminium plates to provide a fixed-base boundary condition. A clearance of approximately 50 mm was maintained between each side of the C-frames and the outer container walls. To stabilise the frames during sand pouring and to prevent soil ingress into the interlayer gaps, T-section supports were installed along both sides of the clearance zone and covered the surface of the top C-frame. In addition, the rear face of the C-frames was isolated from the rigid container wall using three thin PTFE plates, further reducing interface friction. All gaps were covered with tape prior to sand pouring.

The outer span and inner span of a single C-frame is 620 mm and 560 mm, respectivley, with height of 13 mm. Figure 1 illustrates the assembled configuration of the new C-frame Perspex container, comprising 27 stacked frames. The detailed geometry of the container and the locations of the installed instrumentation are shown in Figure 2.

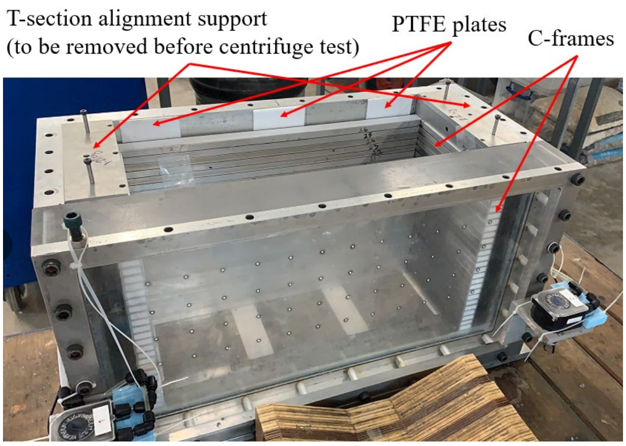

Figure 1. View of the new C-frame Perspex container.

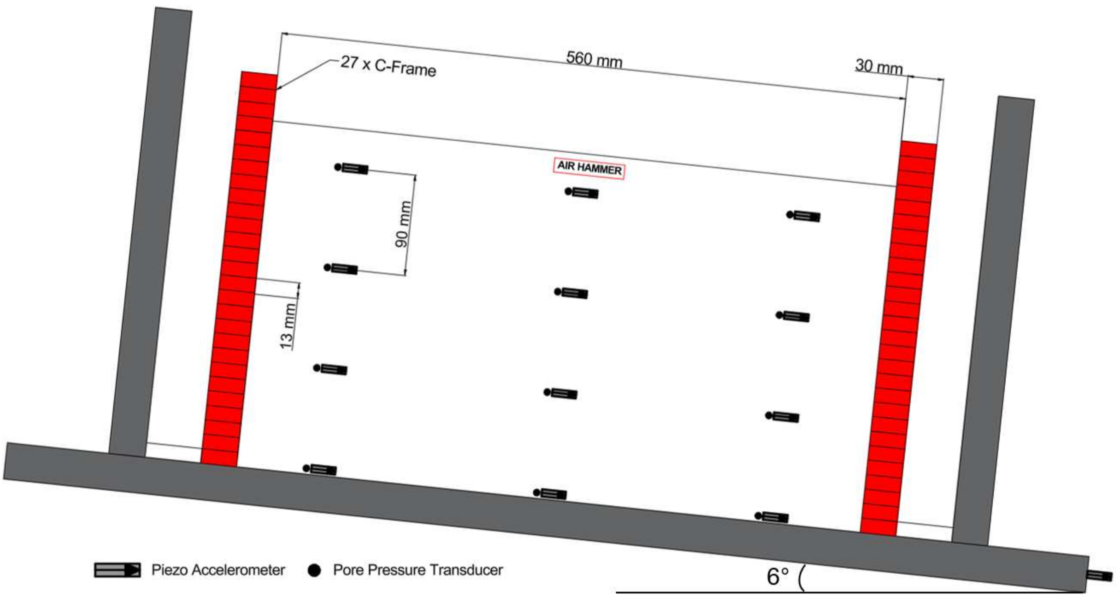

Figure 2. Cross sectional schematic of the centrifuge test model with the new C-frame Perspex container, as seen through the window, instrument locations are also shown.

3 CENTRIFUGE MODELLING

A feasibility test was conducted at 60*g* to evaluate the performance of the newly developed C-frame Perspex container. The test employed a homogeneous sand deposit without any embedded and surface structures, allowing the boundary behaviour of the container to be assessed in a straightforward manner.

The centrifuge model was prepared using loose Hostun HN31 sand (Mitrani, 2006; Haigh et al., 2012) at a relative density of 45%, deposited with an automatic sand pluviation system following the details as described by Madabhushi et al. (2006). The key properties of the model sand are summarised in Table 1. To prevent sand intrusion into the gap between the C-frame ends and the Perspex window, and to minimise unwanted friction that could restrict frame movement, a soft, flexible transparent film was installed along the interface. Finally, the model was saturated under vacuum with methylcellulose using a Raspberry Pi controlled system that is an updated version of the “Cam Sat” system (Stringer and Madabhushi, 2009). The completed centrifuge model with the C-frame container is shown in Figure 3.

Table 1. Properties of Hostun HN31 sand.

Property	Value	Units
D_{10} grain size	0.230	mm
D_{50} grain size	0.325	mm
D_{60} grain size	0.353	mm
Specific gravity (G_s)	2.65	-
Minimum voids ratio (e_{min})	0.555	-
Maximum voids ration (e_{max})	1.010	-
Critical angle of friction (φ_{crit})	34.6	°
Coefficient of uniformity (C_u)	1.57	-

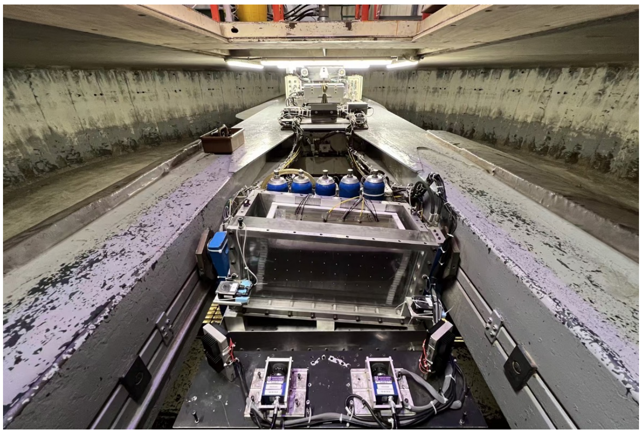

Figure 3. Photograph of the centrifuge model on a 6° slope, view towards the centrifuge pivot.

To control the direction of C-frame deformation, the centrifuge model was mounted on a 6° inclined platform, enabling the resultant frame movement to be predicted and clearly interpreted. A servo-hydraulic shaker (Madabhushi et al., 2012) was used to apply the seismic input motions. The test configurations are summarised in Table 2. The earthquake sequence began with a low-amplitude sine-sweep motion with a peak ground acceleration (PGA) of 0.02 *g* to verify the functionality of the installed instrumentation. This was followed by a recorded Kobe earthquake motion and two 10-cycle sinusoidal inputs with PGAs ranging from 0.14 *g* to 0.19 *g*. These sinusoidal motions generated sufficient cyclic shear strains in the saturated sand to induce significant excess pore pressure buildup, ultimately leading to full liquefaction.

Table 2. Earthquake sequence at prototype scale.

EQ ID	Earthquake			
	Type	Frequency (Hz)	Duration (s)	PGA (g)
CFRAME 02_EQ1	Sine sweep	100 - 0	~70	0.03
CFRAME 02_EQ2	Kobe	~0.5-1.5	~19	0.17
CFRAME 02_EQ3	Sinusoidal	1	~10	0.14
CFRAME 02_EQ4	Sinusoidal	1	~10	0.19

The PIV camera used was the MotionBLITZ EoSens mini 2, model MC 3071, strong LED lights were used to illuminate the windows without flickering effects. Images were captured at 1616×1464 pixels at 635 frames/sec, with a capture time of 1.4 seconds. These images were processed using geoPIV_RG (Stanier et al., 2016). Control point tracking uses point-by-point analysis while soil displacement analysis is done quicker via leapfrogging with Reliability Guided (RG) preconditioned deformation optimisation. Default suggested input parameters were used for geoPIV_RG analysis in MATLAB.

4 DYNAMIC SOIL RESPONSE

The dynamic soil response to the input motion CFRAME02_EQ3 is investigated in this study to evaluate the performance of the newly developed C-frame container. Soil movements were captured using two high-speed cameras mounted on the front gantry, as shown in Figure 3. This configuration ensured comprehensive coverage of the global soil deformation and C-frame response during seismic loading. The soil deformations over half a shaking cycle of CFRAME02_EQ3 on the left and right sides of the model are presented in Figures 4 and 5, respectively. The results show that soil movements are consistent both near the C-frame boundary and in the far field, indicating that the container successfully reproduces an in-situ continuous soil condition.

Some loss of PIV tracking occurred in the regions directly beneath the installed lighting due to reduced soil texture contrast; however, this did not affect the overall interpretation of soil behaviour. Larger lateral deformations were observed when the acceleration was directed downslope, consistent with the imposed boundary inclination. Overall, the test demonstrates the feasibility of the C-frame Perspex container in providing compliant boundary conditions with negligible sand intrusion at the C-frame–Perspex interface, while maintaining full optical accessibility for Particle Image Velocimetry (PIV) analysis.

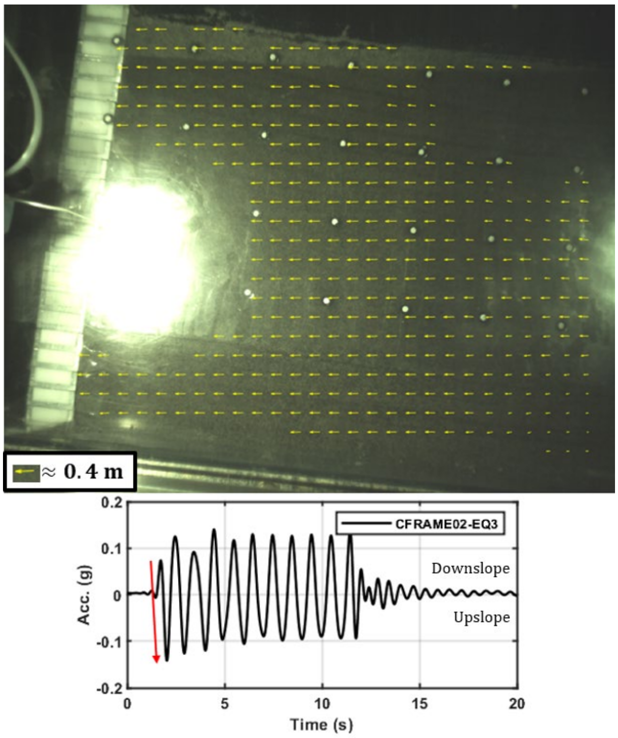

Figure 4. Vector plot of soil deformations on the left side, subjected to half-cycle of shaking, CFRAME02_EQ3.

However, due to the imposed downslope inclination, the water table was slightly below the soil surface, resulting in a small triangular zone of unsaturated soil near the surface that did not liquefy (see Figure 4). This condition affects the accuracy of the interpreted liquefied soil behaviour in the near-surface region, as shown in Figure 4. It should also be noted that the number of C-frames adopted should be sufficient to cover the full soil depth, but not excessive. An overly tall stack of C-frames extending above the soil surface can experience significant displacement during strong cyclic shaking, potentially collapsing into the soil mass and disturbing the test conditions. Careful optimisation of the C-frame height is therefore essential to ensure both stable boundary performance and reliable interpretation of soil behaviour.

The offsets of the C-frames were measured after the centrifuge test and are shown in Figure 6. The results indicate that the frame displacement is consistent with the expected deformation pattern, decreasing progressively with depth due to the increase in lateral earth pressure. The test also confirms that the adopted 50 mm side clearance is sufficient for dynamic centrifuge testing, as adequate space for further frame movement remained even after two strong 10-cycle sinusoidal shaking events.

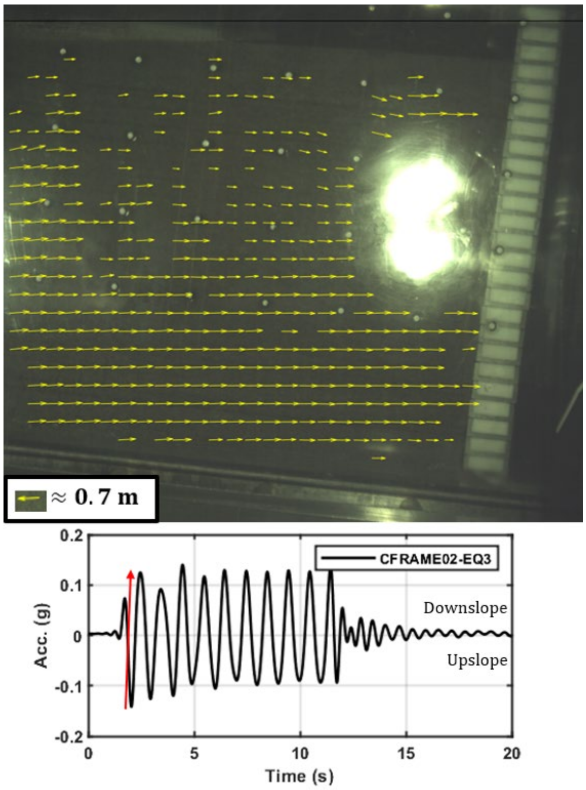

Figure 5. Vector plot of soil deformations on the right side, subjected to half-cycle of shaking, CFRAME02_EQ3.

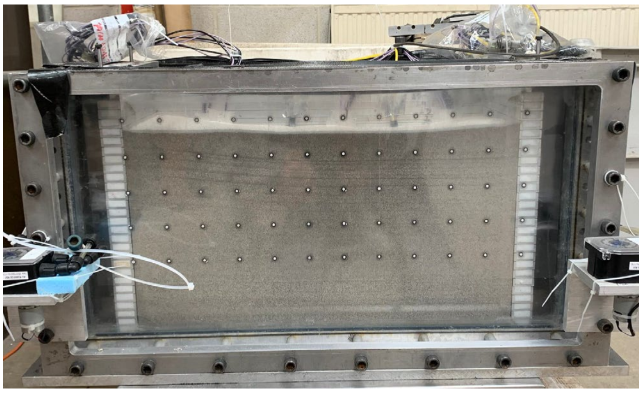

Figure 6a. Photograph of model box pre centrifuge test, prior to saturation.

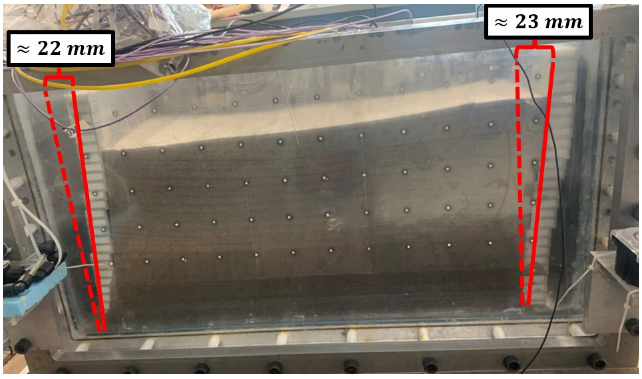

Figure 6b. Photograph of C-frame offset post centrifuge test.

5 CONCLUSION

This paper has presented the development of a novel C-frame Perspex centrifuge container that combines compliant boundary behaviour with full optical accessibility for PIV. By integrating stacked aluminium C-frames with low-friction PTFE interfaces within a rigid Perspex enclosure, the proposed system seeks to replicate in-situ soil response more faithfully than conventional rigid-walled containers, while avoiding the geometric and stiffness limitations of previously proposed transparent laminar or ESB systems.

Results from a feasibility test on a homogeneous loose sand deposit show that the container provides realistic dynamic boundary behaviour under strong seismic loading, including conditions leading to full liquefaction. PIV measurements indicate consistent soil deformation near the boundaries and in the far field, while post-test measurements confirm a depth-dependent C-frame displacement pattern consistent with increasing lateral confinement.

Some limitations were identified that warrant consideration in future applications. The imposed platform inclination, while useful for interpreting frame movement, resulted in a slightly depressed water table and a small near-surface unsaturated zone that did not liquefy. Reflection from the required lights for high speed photography, and soil grain contrast, at times prevented PIV analysis, though this i sbeyond the scope of the current discussion.

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