The paper was published in the proceedings of the 11th International Conference on Physical Modelling in Geotechnics (ICPMG2026) and was edited by Ioannis Anastasopoulos. The conference was held from June 8th to June 12th 2026 in Zurich, Switzerland.

Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

A new apparatus for centrifuge modelling of 3D braced excavations

A.S.N. Alagha
University of Dundee, Dundee, UK, aalagha001@dundee.ac.uk

J.A. Knappett, M. Brown
University of Dundee, Dundee, UK, J.A.Knappett@dundee.ac.uk, M.J.Z.Brown@dundee.ac.uk

C. Augarde, W. Coombs, A. Petalas, M. Ouyang
Durham University, Durham, charles.augarde@durham.ac.uk, w.m.coombs@durham.ac.uk, alexandros.petalas@durham.ac.uk, mao.ouyang@durham.ac.uk

ABSTRACT: Continuous urbanisation has placed ever-increasing demands on transport networks, requiring urban planners and engineers to effectively utilise available underground space. The construction phase of underground infrastructure is typically the most disruptive, as it often entails a significant item of temporary works, a large, braced excavation. This comprises embedded retaining walls supported by a system of temporary props spanning across the excavation as excavation proceeds in a top-down manner. Key design issues for such works are the prediction of ground movements adjacent to the excavation, where neighbouring buildings are often located, and propping forces. While extensive research has focused on 2D modelling of excavations, accounting for 3D effects, which is essential for investigating behaviour at excavation corners, is rarely considered. Improved understanding of corner behaviour and the influences of soil behaviour, system stiffness and propping arrangement could lead to more cost-effective propping strategies, a less congested working volume within the excavation, and improved prediction of ground movements adjacent to corners. This paper presents the design of a new apparatus for 3D centrifuge modelling of braced excavations utilising a trapdoor approach. The new concept incorporates soil-structure interaction for a complete 3D box and enables controlled stress reduction within the excavation in a top-down manner around various propping configurations. This will provide data for validation of future numerical and analytical modelling approaches.

1 INTRODUCTION

Rapid urbanisation and the increasing demand for underground infrastructure have led to widespread use of deep excavations in densely built environments. During construction, these works typically involve large-braced excavations, comprising embedded retaining walls supported by temporary propping systems installed progressively as excavation proceeds in a staged, top-down manner. Although temporary, these systems play a critical role in controlling wall deformation, ground movements behind the excavation which may affect nearby buildings and infrastructure, and construction safety, and they have a decisive influence on construction cost and programme.

Two closely coupled design challenges dominate the engineering of braced excavations: the prediction of wall and ground movements, and the estimation of forces mobilised in the propping system. Overconservative prediction of either response can result in overly dense or heavily loaded propping schemes, restricting access within the excavation and increasing material, installation, and removal costs (Chambers et al., 2016). Reliable prediction of system behaviour is therefore essential, particularly in urban environments where allowable movements are tightly constrained.

Most of the previous research on braced excavations has been based on two-dimensional (2D) plane strain analyses, representing behaviour away from excavation corners. Extensive numerical studies using finite element methods have investigated wall deflections, apparent earth pressure distributions, and prop forces under plane strain assumptions (*e.g.*, Finno et al., 2007; Chambers et al., 2016; Goh et al., 2017). These studies, often calibrated against field monitoring data, have contributed significantly to current design practice and to the development of guidance documents such as CIRIA C760 (Gaba et al., 2017).

However, braced excavations are inherently three-dimensional systems, and the plane strain assumption neglects important spatial effects, particularly at excavation corners. Corners introduce additional stiffness through geometric restraint and load redistribution between orthogonal retaining walls, often enhanced by raking props or corner-specific propping arrangements (see Figure 1).

Several numerical studies (*e.g.*, Chambers et al., 2016; Lu et al., 2023) have demonstrated that neglecting these effects can lead to overestimation of maximum wall deflections and ground movements when using 2D analyses, as the additional system stiffness associated with corner interaction is not captured. Three-dimensional numerical studies, although relatively limited in number, have shown that wall movements and prop loads near corners can be significantly lower than those predicted by equivalent 2D plane strain analyses (*e.g.*, Ou et al., 1996; Zdravković et al., 2005; Dong et al., 2015). As a result, reliance on 2D analyses may lead to overly conservative designs and inefficient propping strategies. Most published 3D studies are limited to a small number of case-specific simulations, restricting their general applicability and their usefulness for developing broad design guidance. Simplified correction approaches, such as plane strain ratio (PSR) methods that relate 3D behaviour to 2D predictions, have therefore been proposed (*e.g.*, Ou et al., 1996; Goh et al., 2017; Lu et al., 2023), but these remain approximate and rely on limited validation data.

Almost all existing centrifuge studies of braced excavations have modelled the problem in a 2D plane strain configuration (*e.g.*, Lam et al., 2012). While these tests have been instrumental in validating 2D numerical models and informing design practice, they inherently exclude 3D effects and cannot capture the stiffness contributions and load redistribution associated with excavation corners.

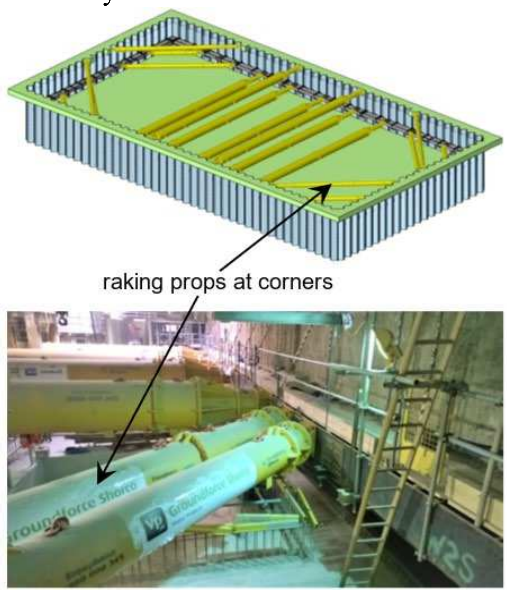

Figure 1. Heavily braced excavation at Crossrail Paddington station (after Chambers et al., 2016).

This paper addresses this gap by presenting the design and development of a new centrifuge apparatus capable of modelling braced excavations in three dimensions. The apparatus enables controlled, staged stress reduction within a fully enclosed excavation box, simulating top-down excavation with a range of propping configurations while capturing full soil–structure interaction effects. The proposed system provides a means to generate high-quality 3D experimental data that can be directly compared with existing 2D and 3D numerical studies and used to validate future numerical and analytical modelling approaches.

2 EXCAVATION GEOMETRY

The excavation geometry considered in this study has been selected to be both representative of real-life braced excavations and compatible with the constraints of geotechnical centrifuge modelling at the University of Dundee.

The planned centrifuge experiments will be conducted at a model scale of 1:100, corresponding to centrifuge accelerations of $100g$. The primary configuration is based on the University of Dundee's long strongbox, which has internal dimensions of 1500 mm (length), 400 mm (depth), and 600 mm (height). At prototype scale, this corresponds to a soil domain approximately 150 m long, 40 m deep, and 60 m high (see Figure 2). The exceptional length of the long box makes it particularly suitable for modelling long, finite excavations, such as may be used for underground construction for rail.

A rectangular excavation geometry is adopted to ensure the presence of four orthogonal corners, enabling explicit examination of three-dimensional wall-wall interaction effects and the influence of increased stiffness at excavation corners. At prototype scale, the planned excavation has plan dimensions of $L = 105$ m and $B = 25$ m, giving an L/B ratio of 4.2 (see Figure 2b). This geometry allows for a clear distinction between corner behaviour and mid-span wall response.

As part of the wider experimental programme, a smaller standard strongbox will also be used to investigate a square excavation geometry with $L = B = 25$ m at prototype scale. These tests are planned at the same model scale and excavation depths; however, this configuration is outside the scope of the present paper, which focuses exclusively on the long rectangular excavation modelled in the long box.

Two excavation depths are planned: 10 m and 20 m at prototype scale, spanning a range typical of deep urban excavations as reported by Long (2001).

In this paper, attention is restricted to the 20 m deep excavation, for which 3D effects and corner-induced stiffness contributions are expected to be most significant.

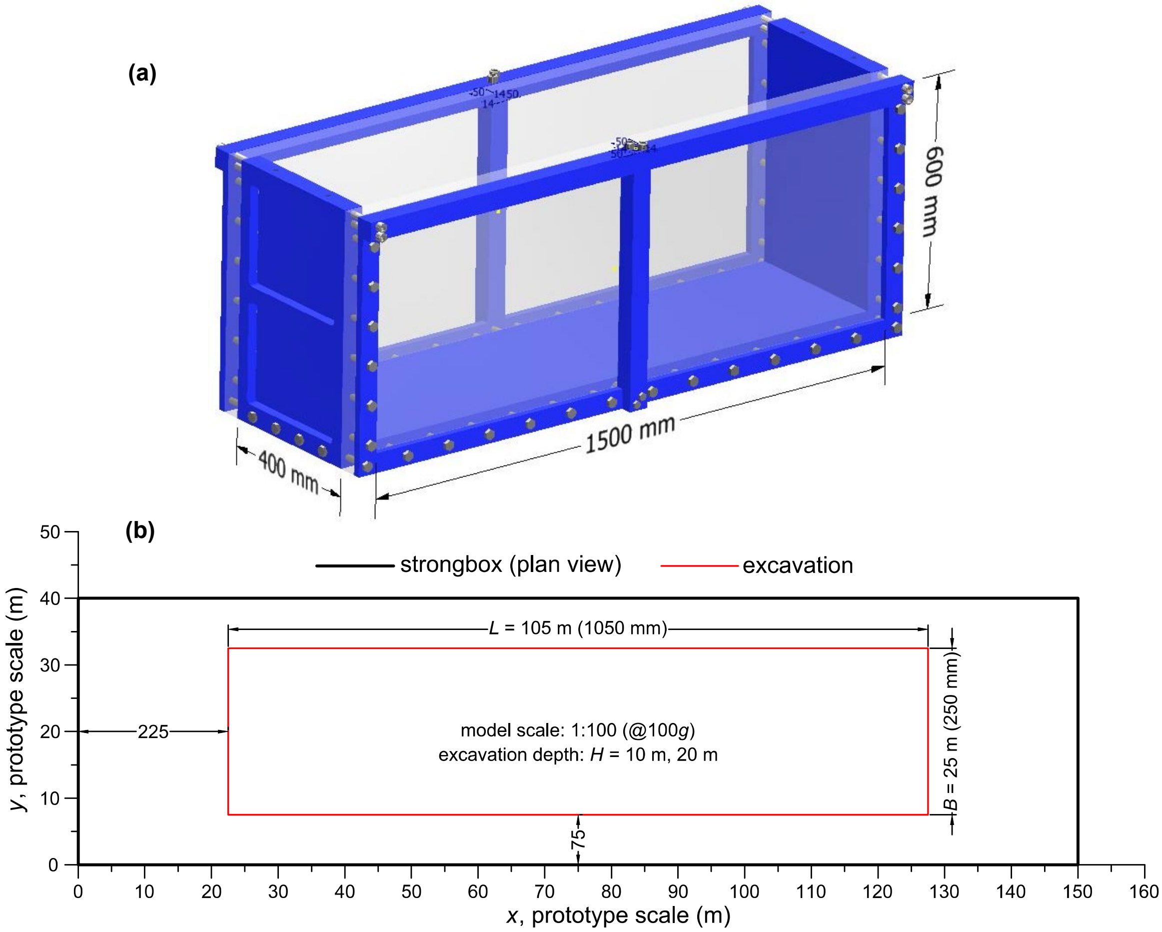

Figure 2. (a) long box dimensions; and (b) excavation geometry at prototype scale.

3 NEW 3D BRACED EXCAVATIONS MODELLING APPARATUS

3.1 Concept

The concept adopted here consists of a trapdoor-based excavation mechanism that allows initially balanced K_0 conditions on either side of the wall, followed by controlled horizontal stress reduction, progressing from top to bottom of the excavation. The apparatus comprises four main components (see Figure 3):

1. a base wall providing structural support and creating a chamber for excavated soil to move into during the test;
2. a horizontal perforated plate supported by the base wall, allowing controlled release of soil through the perforations (see Figure 4b);
3. a braced, instrumented model retaining wall (bracing not shown for clarity); and
4. a movable plate connected to a screw jack (linear actuator) which initially retains soil within the excavation (during spin-up) and displaces downwards to allow controlled soil movement through the perforations in (2) to simulate the excavation process.

As shown in Figure 3a, soil is placed both inside and outside the retaining wall prior to centrifuge spin-up, ensuring that an approximately balanced initial stress state is established on either side of the model retaining wall. Once the target centrifugal acceleration level is reached, excavation is simulated by lowering the moving plate in a controlled manner using the screw jack, which provides precise control of the excavation level throughout the excavation process. As the moving plate is lowered, soil moves through the perforations in the horizontal plate, inducing a controlled reduction in stresses behind the retaining wall until the final excavation depth is reached (see Figure 3b).

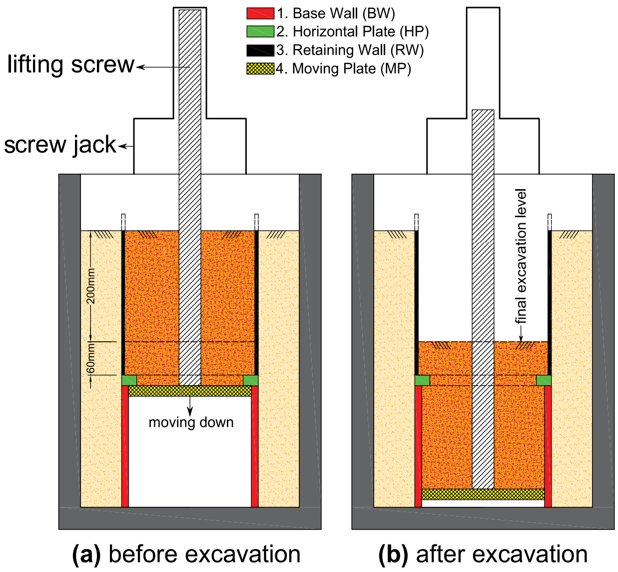

Figure 3. Conceptual representation of the proposed braced excavation modelling apparatus.

This approach enables excavation-induced lateral stress relief to develop in three dimensions, while maintaining soil confinement on all sides of the excavation. The retaining wall is supported at its base by the horizontal plate, simulating a wall founded on competent material such as bedrock. As shown in Figure 3, the planned embedment depth of the wall is 60 mm at model scale, corresponding to approximately one-third of the excavation depth, which is consistent with typical industry practice and guidance (CIRIA C760).

3.2 Experimental apparatus

The braced excavation modelling apparatus developed for this study is shown in Figure 4. The apparatus is designed to realise the excavation concept described in Section 3.1 while ensuring structural stability and precise control during centrifuge operation.

In addition to the four primary components described above, the apparatus includes structural bracing elements (components 5 and 6 in Figure 4) attached to both sides of the base wall. These bracings are essential to restrain the apparatus in the correct position during model preparation and centrifuge loading, preventing any unintended translation or rotation of the base wall under self-weight and soil-induced lateral earth pressure.

Excavation is simulated by lowering the moving plate using two 50 kN screw jacks (sourced from Power Jacks Ltd), arranged symmetrically along the length of the apparatus. The use of two screw jacks is necessary due to the length and weight of the moving plate and overlying soil mass at high gravity; a single actuator would be insufficient to provide stable and uniform control. The screw jacks are operated in mechanical synchronisation, ensuring that stress relief occurs uniformly along the length of the excavation.

The horizontal plate is perforated with large rectangular 'windows' (see Figure 4b), which enables soil to fall through progressively as the moving plate is lowered. The retaining wall is seated directly on the horizontal plate, consistent with the conceptual assumption of a wall founded on competent material.

Given the substantial inertial and soil-induced forces generated during centrifuge testing at 100*g*, The complete system was subjected to a detailed structural assessment using the finite element software ABAQUS (results are not shown here for brevity). In these analyses, the expected loads corresponding to centrifuge acceleration were applied to all structural components, including the base wall, horizontal plate, moving plate, and bracing elements. The thicknesses and material properties of all components were selected such that stresses and deformations remained within acceptable limits at the target acceleration level, providing confidence that the apparatus can safely withstand the demands of high-*g* centrifuge operational levels.

4 DESIGN OF DEEP EXCAVATION SUPPORT SYSTEM

The deep excavation support system (bracing) in urban environments (which typically comprises an embedded retaining wall supported by a combination of horizontal and corner props) must be designed to maintain acceptable levels of wall movement under the imposed loading conditions. This section outlines the design considerations adopted for the excavation support system that will be used in the experimental programme planned for this study.

4.1 Propping layout and configuration

The planned propping layout adopted in this study is illustrated in Figure 5, which shows the configuration of the excavation support system.

The layout has been selected to be representative of typical practice in deep urban excavations, while allowing controlled investigation of three-dimensional stiffness effects, particularly at excavation corners.

Figure 5a shows the horizontal distribution of props. Intermediate horizontal props are provided along the length of the retaining walls, together with raking props at each excavation corner. The inclusion of corner props reflects common practice in large, braced excavations. The horizontal spacing between adjacent props is 90 mm at model scale, corresponding

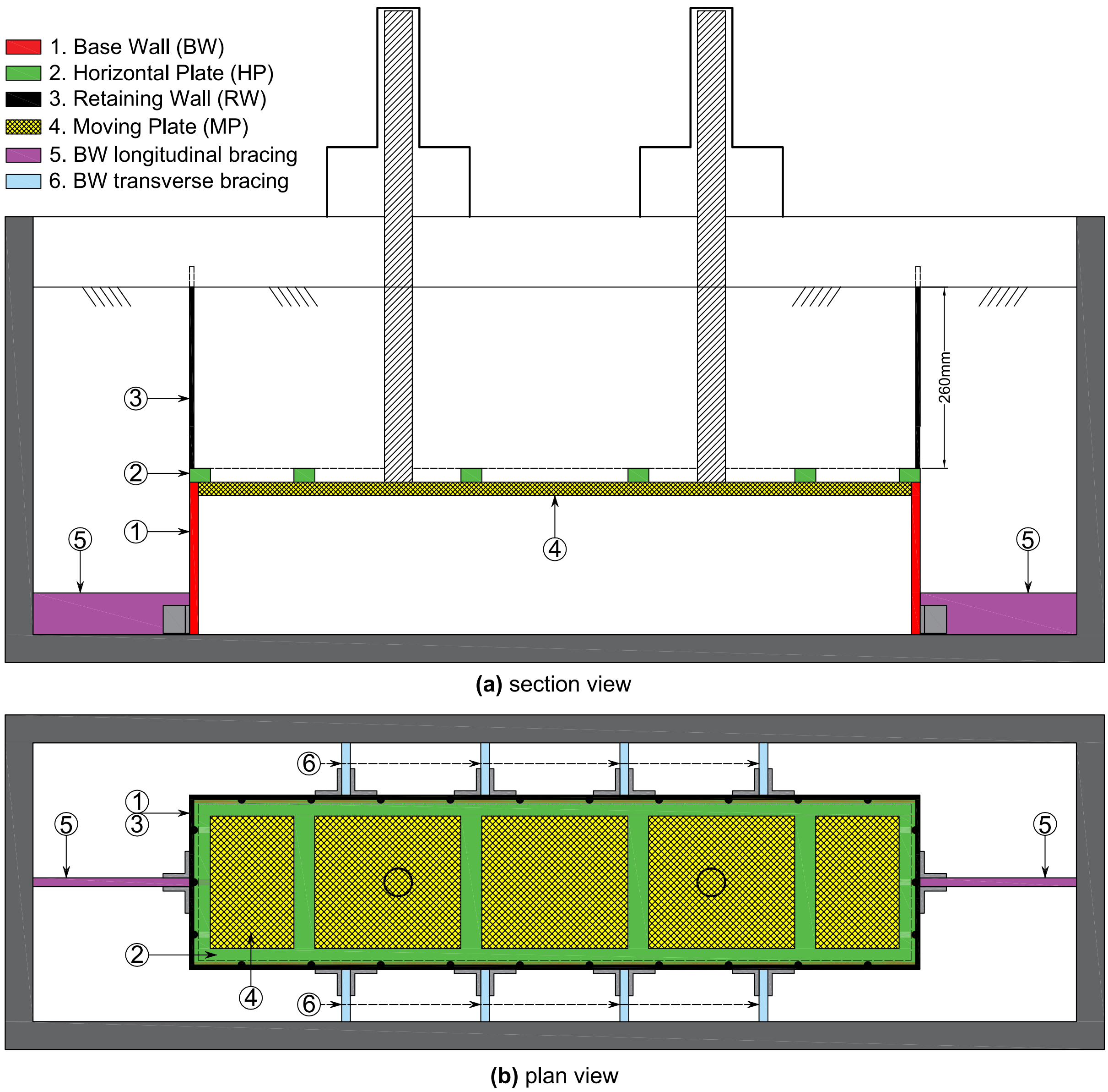

Figure 4. Main components of the three-dimensional braced excavation modelling apparatus.

to 9 m at prototype scale. This spacing lies within the range commonly reported for large, braced excavations and is consistent with values adopted in published case histories and numerical studies (*e.g.*, Chambers et al., 2016; Latapie et al., 2017). The corner raking props are intended to enhance corner restraint and increase overall system stiffness, replicating the structural behaviour observed in practice.

The vertical layout of props is shown in Figure 5b, which presents a cross-sectional view of the excavation. The initial design includes four levels of propping. The top prop level is located 10 mm below the ground surface at model scale, equivalent to 1 m at prototype scale, representing a top prop commonly used to control near-surface wall movements. Subsequent prop levels are spaced at 50 mm intervals at model scale, corresponding to 5 m at prototype scale. This vertical spacing is consistent with typical values reported in the literature, particularly with a large field database compiled by Long (2001).

4.2 Retaining wall design

This section presents the design of the retaining wall and associated propping system adopted in this study. Two design cases are considered: an excavation representative of typical construction practice and a centrifuge configuration developed for the planned physical modelling programme; both cases are defined at prototype scale for valid comparisons. The objective is to define a centrifuge testing configuration that reproduces the response of the reference excavation.

The design process is iterative and is undertaken using Oasys FREW (Flexible REtaining Walls) software (Oasys Ltd, 2022), which is widely used in

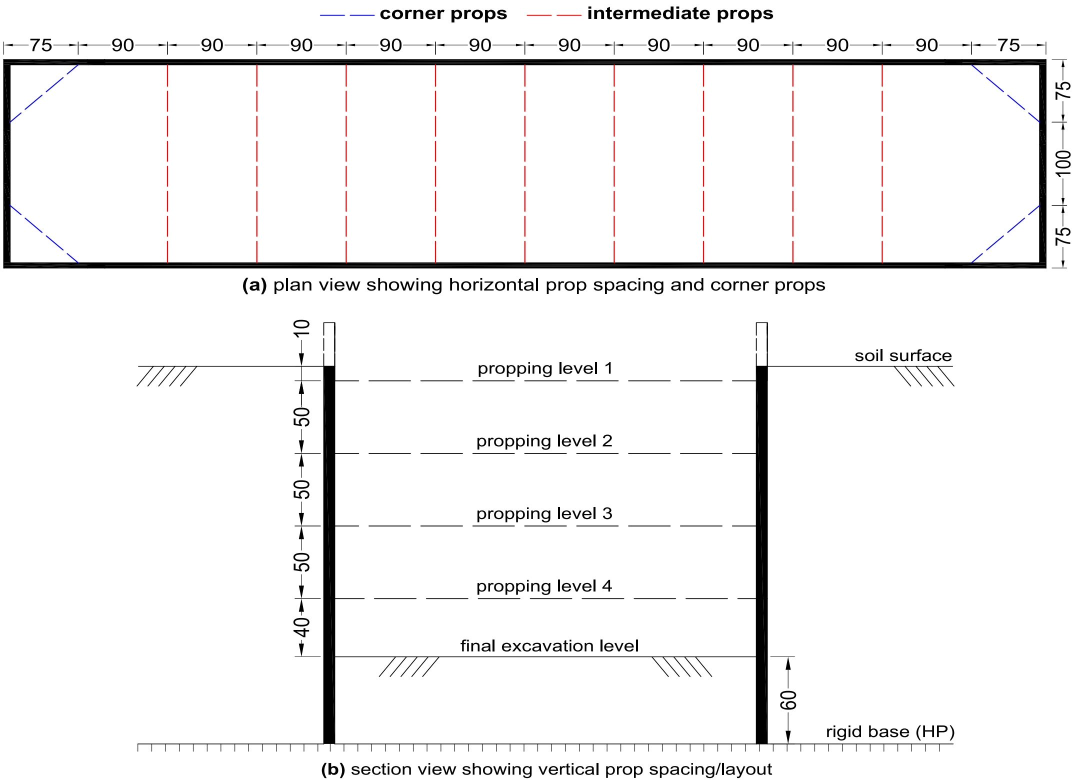

Figure 5. Horizontal and vertical prop spacing.

UK practice and was recommended by the project's industry partners. Equivalence between the two cases is primarily established through iterative comparison of propping requirements and construction sequence, with wall displacement profiles used as the principal comparison metric, as this is both the primary performance metric for braced excavations in design and as this directly controls the mobilisation of lateral stress changes during excavation.

4.2.1 Soil properties and scaling

Looking first at the centrifuge case, the tests are designed to be conducted on a 1/100 scale braced retaining wall in saturated sand at 100g. In such tests, the vertical effective stress is $\sigma'_v = \rho' G_{sat} z$, where G_{sat} is the centrifugal acceleration in saturated sand, (*i.e.*, $G_{sat} = 100\text{g}$); ρ' is the buoyant density of saturated soil (*i.e.*, $\rho' = \rho_{sat} - \rho_w$); and z is the depth of soil in a 1/100 scale model.

In the design and analysis of retaining walls, vertical and horizontal effective stresses are the primary quantities of interest. It was therefore recognised that dry sand could be conveniently used in place of a more common saturated condition in the planned centrifuge tests, significantly simplifying model preparation. To ensure equivalent stress conditions, the vertical stress of dry sand expressed as $\sigma_v = \rho_d G_d z$ must be made equal to the vertical effective stress of saturated sand (*i.e.*, σ'_v), where G_d is the centrifugal acceleration to be used in a dry sand test; ρ_d is the dry density of the sand; and z is the depth of soil in a 1/100 scale model. This means that G_d can be expressed as:

$$G_d = \frac{\rho'}{\rho_d} G_{sat} \quad (1)$$

The sand intended to be used in the centrifuge tests is HST95 Congleton silica sand (Al-Defae et al., 2013), with an average relative density of $I_D = 60\%$ to obtain a uniform, medium-dense soil layer. Throughout a series of oedometer tests, Al-Defae et al., 2013 produced empirical equations that directly link the relative density to both dry and saturated unit weights of sand. At $I_D = 60\%$, the dry and saturated densities are thus computed as 1662 kg/m^3 and 2027 kg/m^3, respectively. Substitution of these values in Equation 1 implies that centrifuge tests on dry sand should be performed at 62g to reproduce the same effective stress profile of saturated sand tested at 100g. This modelling technique has been successfully adopted in previous studies (*e.g.*, Li et al., 2010).

For the reference excavation, representing typical construction practice, the soil is assumed to be fully saturated with $\rho_{sat} = 2027\ kg/m^3$.

4.2.2 Wall thickness and stiffness

The retaining wall selected for this study is a diaphragm wall, reflecting its widespread use in the UK and internationally for deep urban excavations. The choice of wall thickness was informed by published field data. Long (2001) compiled an extensive database relating excavation depth to diaphragm wall thickness, from which a wall thickness of 0.6 m was selected as representative. This value lies close to the mean of reported practice and is appropriate for both excavation depths considered in this study (10 m and 20 m).

For centrifuge modelling at a scale of 1:100, the corresponding model-scale wall thickness is 6 mm. As this thickness is difficult to source commercially, a 6.35 mm (¼ inch) thick aluminium alloy (grade 6082-T6) wall section is adopted for the centrifuge tests, providing a close approximation to the target scaled thickness.

Wall behaviour is governed primarily by its flexural stiffness, EI. In practice, it is common to account for cracking, creep, and stress redistribution by adopting a reduced effective stiffness. Current UK guidance (CIRIA C760) recommends values of 0.7EI for short-term construction stages and 0.5EI for long-term conditions. Consistent with this guidance, the wall stiffness adopted in this study is taken as 0.5EI, where EI is 540 MN.m^2 per meter run of the wall.

4.2.3 Construction sequence and prop stiffnesses

The analyses of the two cases were implemented using Oasys FREW software.

For the reference case, the construction sequence represents a conventional top-down excavation. Excavation proceeds in stages, with props installed progressively, in an initially unloaded case, as excavation advances. A total of four prop levels are considered. After excavating the first two meters, the top prop is installed at 1 m below the ground surface. Subsequent props are installed at 5 m vertical spacing after 5m excavation stages, consistent with typical practice, until the final excavation depth is reached. The prop axial stiffness of the reference case was estimated as 83,000 kN/m per metre run of wall. This was found to be an average value of the cases reported by CIRIA C760 and Latapie et al. (2017).

For the centrifuge case, due to the complexity of the experimental apparatus and the constraints of centrifuge operation, all props are pre-installed prior to centrifuge spin-up, and excavation is simulated solely through staged stress relief. The excavation proceeds in 5 m prototype-scale stages, while all pre-installed props remain active throughout the excavation process. To achieve the closest possible equivalence with the reference case in terms of wall deformations, the prop stiffness and number of prop levels in the centrifuge model were varied iteratively. These parameters were adjusted until an acceptable match was achieved between the wall displacement profiles of the reference and centrifuge cases.

4.2.4 Results and final propping configuration

For the reference case, a single analysis was performed in FREW following the construction sequence described in Section 4.2.3. For the centrifuge case, an iterative design process was undertaken. Initial analyses assumed four pre-installed prop levels, matching the number used in the reference case. This configuration resulted in very small wall displacements, indicating an overly stiff system relative to the reference excavation. Consequently, the number of prop levels in the centrifuge model was reduced to two (see Figure 6).

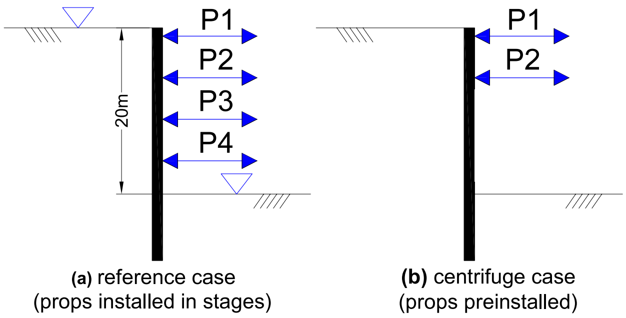

Figure 6. Final propping configuration

Following this adjustment, the axial stiffness of the two props was varied iteratively until an acceptable match was achieved between the wall displacement profile of the centrifuge case and that of the reference case. Through this process, the final prop stiffness values adopted for the centrifuge configuration were 40 $\mathrm{kN/m/m'}$ for the upper prop and 8.5 $\mathrm{kN/m/m'}$ for the lower prop.

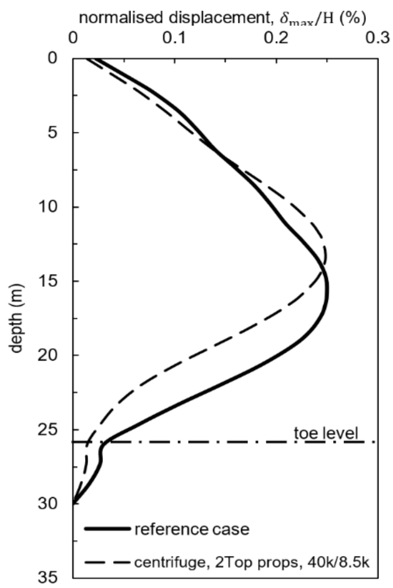

Figure 7. Comparison of displacement profiles

This configuration produced wall displacement profiles that closely matched those of the reference case as shown in Figure 7. The maximum normalised wall displacement obtained is approximately 0.25% of the excavation depth, which is comfortably below the upper bound of 0.4% reported by Long (2001).

5 CONCLUSIONS

This paper has presented the design and development of a novel three-dimensional experimental apparatus for centrifuge modelling of braced excavations. The paper outlined the motivation for three-dimensional modelling, described the excavation geometry, the experimental concept, and the apparatus design, and presented the propping layout and retaining wall design adopted for centrifuge implementation. An iterative design process was used to define a final propping configuration for the centrifuge model that reproduces displacement behaviour consistent with a representative (staged) field excavation. The proposed apparatus enables systematic investigation of corner effects and three-dimensional stiffness contributions, providing experimental data that are currently lacking in the literature and that are essential for validating advanced numerical and reduced-order modelling approaches. Future work involves apparatus assembly and a series of centrifuge experiments. Ultimately, this work contributes to improved understanding of corner behaviour in braced excavations and supports the development of more efficient and cost-effective design guidance.

ACKNOWLEDGEMENTS

This work was inspired by funding made available from the Engineering and Physical Sciences Research Council for Durham and Dundee Universities [grant numbers EP/X024849/1 \& EP/X024768/1].

REFERENCES

Al-Defae, A. H., Caucis, K., & Knappett, J. A. (2013). Aftershocks and the whole-life seismic performance of granular slopes. *Géotechnique*, *63*(14), 1230-1244.

Chambers, P., Augarde, C., Reed, S., & Dobbins, A. (2016). Temporary propping at Crossrail Paddington station. *Geotechnical research*, *3*(1), 3-16.

Dong, Y., Burd, H. J., & Houlsby, G. T. (2017). Finite element study of deep excavation construction processes. *Soils and foundations*, *57*(6), 965-979.

Finno, R. J., Blackburn, J. T., & Roboski, J. F. (2007). Three-dimensional effects for supported excavations in clay. *Journal of Geotechnical and Geoenvironmental Engineering*, *133*(1), 30-36.

Fuentes, R., & Devriendt, M. (2010). Ground movements around corners of excavations: empirical calculation method. *Journal of geotechnical and geoenvironmental engineering*, *136*(10), 1414-1424.

Gaba A, Hardy S, Doughty L, Powrie W and Selematas D (2017) Guidance on Embedded Retaining Wall Design. Construction Industry Research and Information Association, London, UK, C760.

Goh, A. T. C., Zhang, F., Zhang, W., Zhang, Y., & Liu, H. (2017). A simple estimation model for 3D braced excavation wall deflection. *Computers and Geotechnics*, *83*, 106-113.

Lam, S. Y., Elshafie, M. Z., Haigh, S. K., & Bolton, M. D. (2012). A new apparatus for modelling excavations. *International Journal of Physical Modelling in Geotechnics*, *12*(1), 24-38.

Latapie, B., Winarta, T., & Lloyd, S. D. (2017). Benefits of pre-loading temporary props for braced excavations. *Geotechnical Research*, *4*(3), 178-191.

Li, Z., Haigh, S. K., & Bolton, M. D. (2010). Centrifuge modelling of mono-pile under cyclic lateral loads. *Physical Modelling in Geotechnics*, *2*, 965-970.

Long, M. (2001). Database for retaining wall and ground movements due to deep excavations. *Journal of Geotechnical and Geoenvironmental Engineering*, *127*(3), 203-224.

Lu, T., Wu, K., Liu, S., & Cai, G. (2023). Method for estimating three-dimensional effects on braced excavation in clay. *Tunnelling and Underground Space Technology*, *141*, 105355.

Oasys Ltd. (2019). *Frew: Embedded Retaining Wall Analysis Software* (Version 19.4) [Computer software]. https://www.oasys-software.com/products/frew/

Ou, C. Y., Chiou, D. C., & Wu, T. S. (1996). Three-dimensional finite element analysis of deep excavations. *Journal of Geotechnical Engineering*, *122*(5), 337-345.

Roboski, J., & Finno, R. J. (2006). Distributions of ground movements parallel to deep excavations in clay. Canadian geotechnical journal, 43(1), 43-58.

Zdravkovic, L., Potts, D. M., & St John, H. D. (2005). Modelling of a 3D excavation in finite element analysis. *Géotechnique*, *55*(7), 497-513.