A simple modular system for undergraduate laboratory experiments using a large geotechnical centrifuge.

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ABSTRACT: Simple centrifuge modelling experiments that replicate classical geotechnical failure mechanisms form a valuable component of an undergraduate education program. This paper describes a set of apparatus and experimental procedures developed at the University of Southampton to support laboratory experiments in the geotechnical modules of the undergraduate Civil Engineering program. The apparatus is designed to be modular and easily handled by students, to maximise the efficiency and the hands-on nature of the activity. The paper describes the miniature modular and stackable strongbox system that can be configured to allow up to nine samples to be tested concurrently, the procedures used for efficient model construction, and the set of geotechnical models that represent walls, foundation and other systems, for which stability predictions can be made prior to the students observing their own model being tested. These experiments benefit students in many ways. Primarily they strengthen the understanding of the underlying geotechnical analysis methods, by applying them to a real failure that they conduct and observe. The students also get hands-on familiarity with soil sample preparation and characterization methods. Finally, there are also cohort-building and peer-to-peer learning benefits from this type of group work in a laboratory setting.

1 INTRODUCTION

1.1 Hands-on teaching of geomaterials

Hands-on laboratory demonstrations play an important role in engineering education as they allow students to test and reinforce the theoretical knowledge gained during lectures. In contrast to other fields, geotechnical engineering presents a challenge, as it is difficult to replicate real-world scenarios in a lab environment. Kolb (1984) introduced the concept of the "experimental learning cycle", which highlights that learning is a continuous process involving experience, reflection, conceptual understanding, and experimentation, rather than a straightforward sequence.

In geotechnical education, as offered in the Civil Engineering program in Southampton, timetable geotechnical laboratory classes initially focus on soil classification description during the first year, and then moves into engineering parameter assessment (compressibility, permeability and strength) via oedometer and triaxial tests in the second year. In contrast to many engineering courses, where laboratory access is increasingly restricted, our students continue to conduct these tests in pairs, live in our geomechanics laboratory, and interpret the data for formative or summative coursework submissions. This provides a strong practical grounding in the fundamental behaviour of geomaterials. However, a limitation of these first- and second-year laboratory classes is that they do not expose students to the behaviour of geotechnical structures, such as slopes, retaining walls and foundations.

Accurately replicating the behaviour of these structures using small scale 1g bench models is challenging because the correct stress conditions of full-size structures are not recreated, limiting the realism of the response and preventing gravity-driven failures from being easily generated.

However, applying increased gravitational forces in a centrifuge provides realistic geostatic stress conditions, particularly benefiting those failure mechanisms caused by the weight of the geomaterial. As a result, models can better replicate realistic stresses and strain patterns, revealing failure mechanism that can be compared to theoretical solutions taught in class.

1.2 Teaching via miniature centrifuges

Because of these benefits, miniature geotechnical centrifuges have been used very successfully as part of a geotechnical education program, allowing students to recreate failure mechanisms in convenient small experiments. A key benefit of miniature geotechnical centrifuges is that students are able to prepare, assemble and conduct the experiments with minimal supervision, due to the small size, weight and reduced risks associated with miniature machines.

Notable examples of UK miniature geotechnical centrifuge operations used in education are the University of Dundee (Newson et al. 2002, Newson & White 2005) and University of Sheffield (Black 2014) facilities. These small beam centrifuges feature a swinging basket that contains an approximately cubic sample with dimensions typically 0.1-0.15m, resulting in samples that weigh 2-3 kg at 1g.

These mini-centrifuges have been used to provide timetabled laboratory activities to undergraduate or master's level students, as well as hosting student projects. Projects using these miniature centrifuges make parametric centrifuge modelling studies accessible as BEng, MEng or MSc student projects, without the major overhead of staff support, time and cost associated with using a larger machine.

These advances have been accelerated by the reducing cost of sensors, including cameras for imaging, and the increasing scope for miniaturisation in component manufacturing and instrumentation. Together these wider trends in mechatronics and image analysis continue to raise the fidelity and data richness of smaller physical models (White 2020).

1.3 University of Southampton initiative

The University of Southampton has recently commissioned a 150 g-tonne 6m-diameter geotechnical centrifuge, as part of the National Infrastructure Laboratory (NIL) – a UK government-funded initiative to raise the UK's capability for research into infrastructure and cities (Mendoza-Ulloa & White 2024).

This machine is an Actidyn Systemes model C67-4 (Figure 1). This centrifuge has a maximum acceleration of 130 g at 208 rpm and features a basket at the end of the beam that can accommodate a payload of up to 1500 kg at 100 g or 950 kg at 130 g.

Figure 1. Actidyn C67 centrifuge at the National Infrastructure Laboratory, University of Southampton.

The basket platform has plan dimensions of 1 m × 0.8 m and the height of the payload can be of up to 1.3 m. This size is well-suited to research applications but is not ideal for teaching use due to the large scale and mass of samples and model packages.

This paper describes a new experimental set-up that overcomes this limitation in a way that allows up to 9 small groups of students to build and test models on the centrifuge at the same time. This is achieved using smaller sample sizes, assembled together, making the centrifuge more suited to undergraduate teaching and student project use.

This new capability addresses the limitations of scale and space requirements associated with models that use the full size of the usual strongbox, while utilising the existing centrifuge, and associated systems. In this way the undergraduate learning of geotechnical engineering can encompass Kolb's "experimental learning cycle"

The paper introduces: (i) the centrifuge facility, and outer large strongbox, (ii) the design and assembly of the miniature student strongbox, (iii) the procedures and arrangement for combining multiple models in a single test spin and (iv) the typical student experiments used to introduce various geotechnical engineering principles.

2 CENTRIFUGE DETAIL

2.1 Centrifuge arrangement and platform size

The geotechnical centrifuge is located in the basement of the National Infrastructure Laboratory alongside, facilities for clay mixing, sand pouring and sample preparation. On the floor above, accessed via a lift or stairs, is the centrifuge preparation laboratory, and the centrifuge control room. This lab has as bench arrangement that can accommodate a group of students during timetabled classes, with facilities for projecting slides for teaching and instruction. In addition, the prep lab has bench stations for 1g testing, as well as electronics, sample preparation and other activities.

The platform of the centrifuge basket has dimensions of 1 m × 0.8 m. The operating approach for teaching use is for an outer strongbox to be kept on the centrifuge basket while miniature strongboxes – with weights that are well below the limit for manual handling – are added and removed for testing. This eliminates the need for heavy lifting operations, saving time and reducing the reliance on trained personnel.

2.2 Primary strongbox description

The primary strongbox in which the miniature strongbox setup is constructed has external dimensions of 930mm (length) × 730mm (width) × 585mm (depth), with an internal usable sample space of 700mm × 580mm × 500mm. This size corresponds to a maximum volume of 130m × 140m × 104m at prototype scale, with the sample mass being typically 200 kg if the container is half-filled. This scale is unsuitable for undergraduate experiments.

3 MINIATURE STRONGBOX SYSTEM

3.1 Description and manufacture

A more suitable scale of model is provided by a set of miniature rectangular prismatic strongboxes (Figure 2, Figure 3). These miniature strongboxes are designed to fit into the main outer strongbox, at one end. The outer dimensions of these miniature strongboxes are such that 3 × 3 grids of them can be stacked at one end of the outer strongbox and be observed concurrently from the opposite end of the strongbox.

The outer dimensions of the miniature strongbox are 160mm (width) × 125mm (depth) × 160*m*m (height), with internal dimensions of 128mm × 75mm × 139mm. This size corresponds to a maximum prototype plan area of 23m × 16.8m and a maximum prototype depth of 28.9m. This is sufficiently large to represent a prototype slope, tunnel or foundation system.

The body of the miniature strongbox is made from aluminium, while both sides are windows made from acrylic, retained by aluminium frames. The assembly components are designed to be modular and suitable for rapid assembly and disassembly. Also, individual components can be changed out if future variations in dimensions or features are required.

Each side component features six threaded entry ports for instrumentation wiring, or for other experimental features to enter the container. In addition, there are six threaded holes on the top surface of the box. These provide a mounting point for brackets to support cameras or fix other experiment components onto the strongbox. Or, when using the strongboxes in a stacked arrangement, these holes are for the attachment of locating pins. These pins fit into clearance holes that are included at the corners of the underside of the base component.

The sides and frames bolt to each other and the bottom component. Liquid sealant is used to seal between the bottom component and the side component, which are usually kept assembled during model preparation and disassembly. These components are referred to as the U-frame. A gasket is used to seal between the U-frame components, and a rubber O-ring is used to seal between the U-frame and the acrylic window panels.

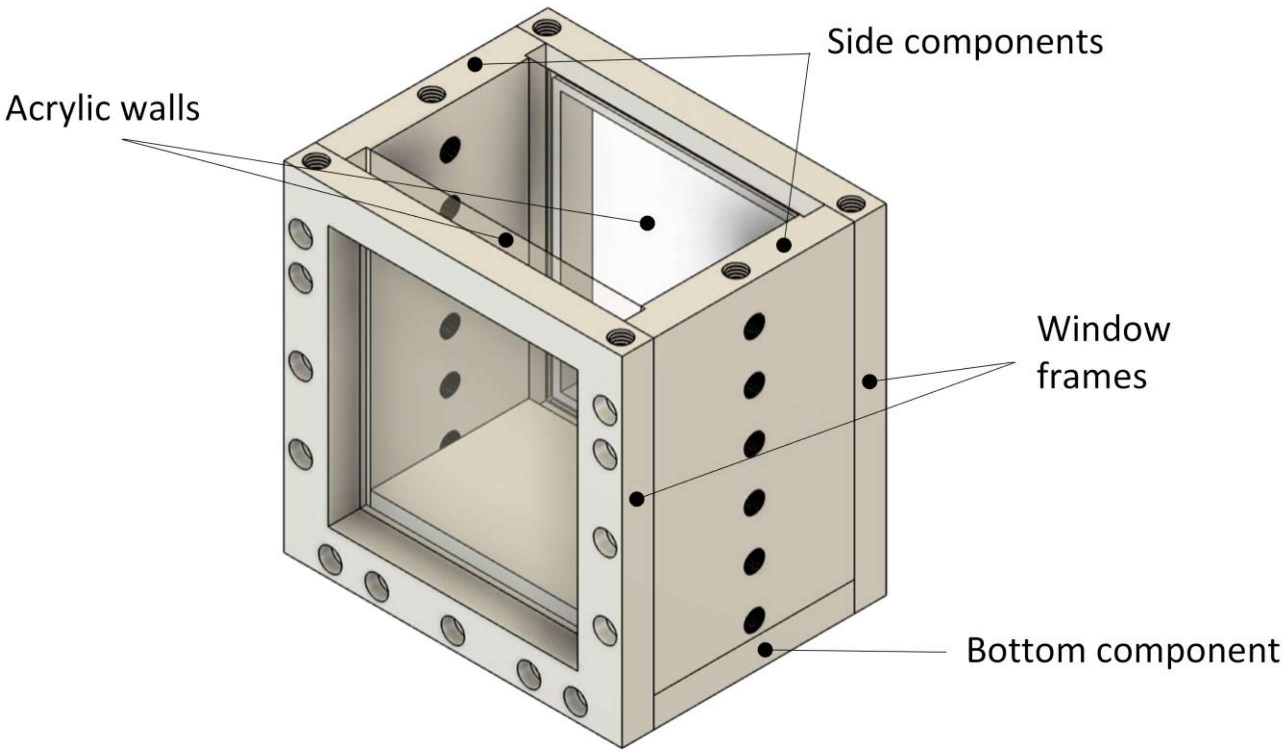

Figure 2. Miniature strongbox: CAD illustration.

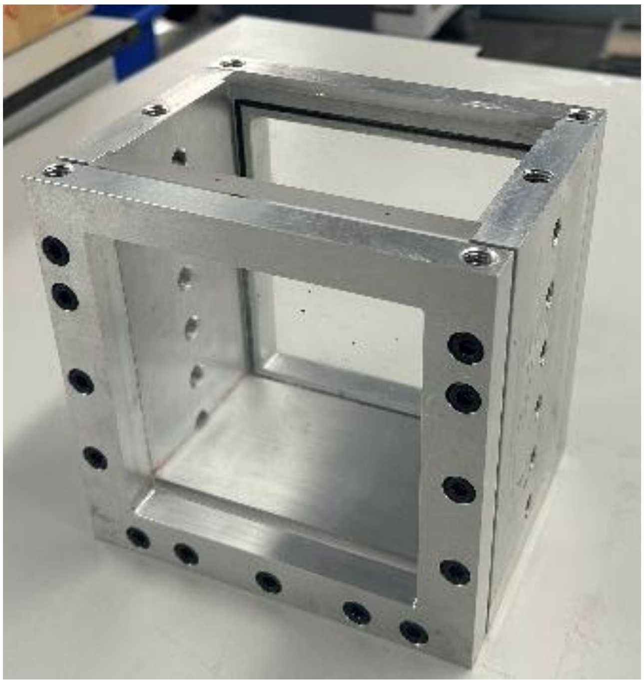

Figure 3. Miniature strongbox: Photograph.

The window frame and the acrylic are separate components so that the acrylic be easily changed out if scratched and unsuitable for accurate imaging for DIC or PIV testing. Similarly, if an opaque side panel is required, or a panel with entry ports for instruments and other experimental features, these need only be fabricated into a rectangular sheet, which can be retained behind the aluminium frame.

The fully-assembled strongbox, with front and rear windows, has a mass of 3.4kg. When completely filled to the brim with dense soil ($\rho = 2\ t/m^3$), the mass is 6.0kg. With a more typical model, filling half of the strongbox volume, the mass is 4.7kg – which is a manageable weight for manual handling by individual students, without special training or safety measures.

3.2 Assembly of miniature strongbox

The initial assembly procedure for the miniature strongboxes involves careful installation of the U-frame gasket. To achieve this, the bottom component is placed on a flat surface, with the window frames positioned around it, enclosing the base. The side components are then placed on top of the bottom piece, and the frame is screwed to the side components.

Next, the bottom component is removed and liquid sealant applied along the edges of the bottom component along both sides of the screw holes. The frame is then repositioned on top of the bottom component, and these components are screwed together. At this point, the window frame is removed, leaving the U-frame, and the assembly is left to dry for 24 hours to allow the sealant to reach full strength.

Next, the box is sealed at the side frames and acrylic windows. The acrylic is sealed to the side frame using an O-ring with silicon lubricant to ease placement of the O-ring and improve its durability. The frame is sealed to the side component with a rubber gasket cut into the U-shape, slightly undersized. This allows the material to expand laterally when compressed.

This assembly arrangement allows the U-frame to remain assembled while the window frame and acrylic windows are removed for sample preparation or removal. Clear instructions are provided for student use – such as advice on the tightening sequence for the screws, initially alternating between opposite corners and progressing around the frame on alternate sides, ensuring that the O-ring is compressed evenly and the box seals completely.

3.3 Testing configuration: stacked strongboxes

The configuration of multiple miniature strongboxes assembled for concurrent testing is shown in Figure 4. The 3 × 3 arrangement allows all tests to be concurrently viewed through the strongbox windows. The sizing of the strongboxes provides a gap of ≈15mm between strongboxes, easing their placement. Locating pins attach to the top corners of the lower two rows of strongboxes, making alignment simple.

For teaching applications, the tests involve gravity turn-on of self-weight loading, via a slow progressive increase in the centrifuge acceleration. In these tests there is no need for any actuation within each strongbox, or supply of fluid. However, the spacing between the miniature strongboxes and the side ports means that more complex modelling can be conducted using the multiple stacked test approach – for example, by introducing control of the water table via fluid supply to each strongbox through the side ports.

At the opposite end of the outer strongbox is a scaffolding system to support one or multiple cameras. The scaffolding system is shown via CAD on the left of Figure 4 and in a photograph on the right of Figure 4. This scaffolding system is modular and fabricated in 3D-printed plastic (Figure 6). It can be assembled by hand without bolting, in a range of configurations, to suit different fields of view and different camera and lens combinations.

The camera connections are via conventional quarter-inch threads through slots that allow flexible positioning. The scaffold components also feature cable management connection points.

A wooden baseplate is placed in the outer strongbox, to which a set of 3D-printed plastic guides are attached, ensuring correct positioning of the strongboxes and camera scaffolds (Figure 4, right).

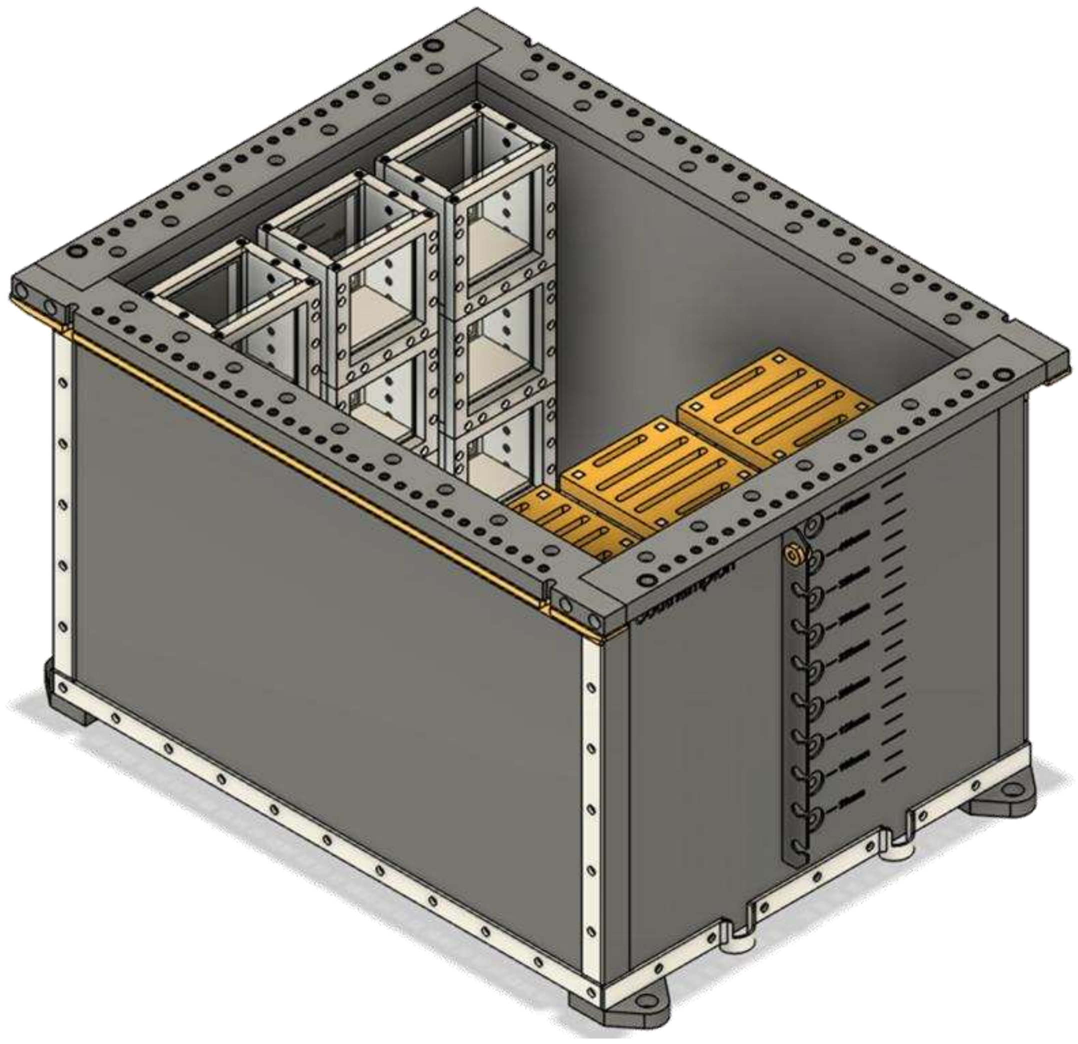

Figure 4. Miniature strongboxes stacked within outer strongbox: CAD.

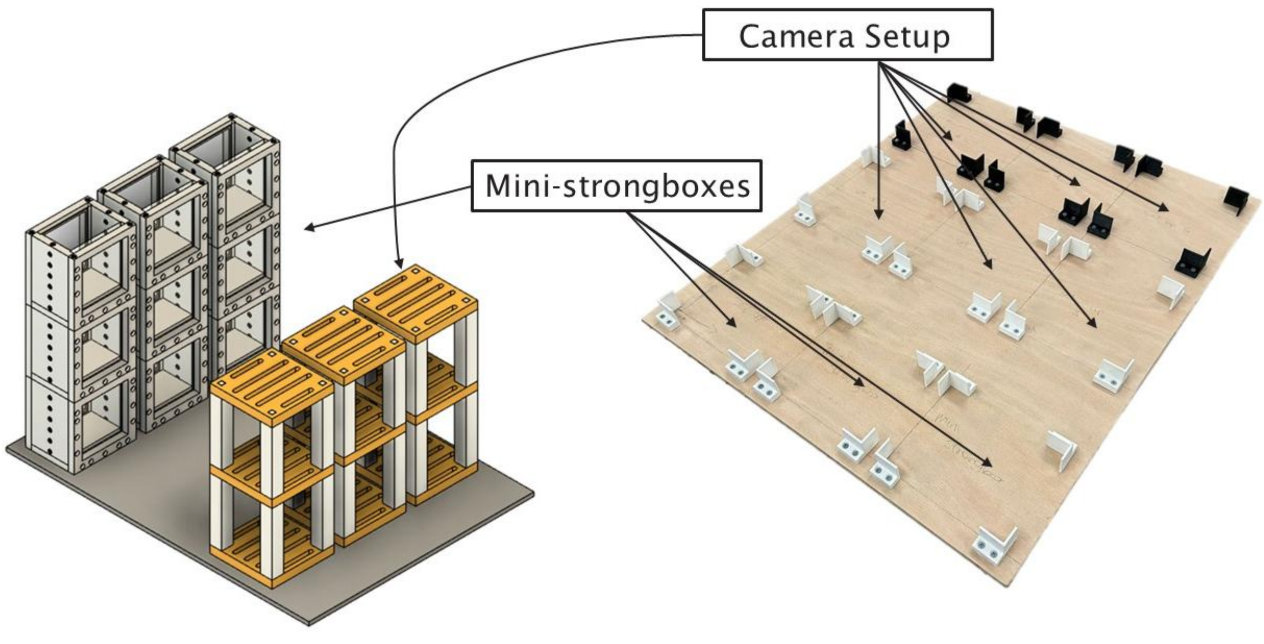

Figure 5. Stacked miniature strongboxes: CAD with outer box removed (left) and support plate with alignment guides (right).

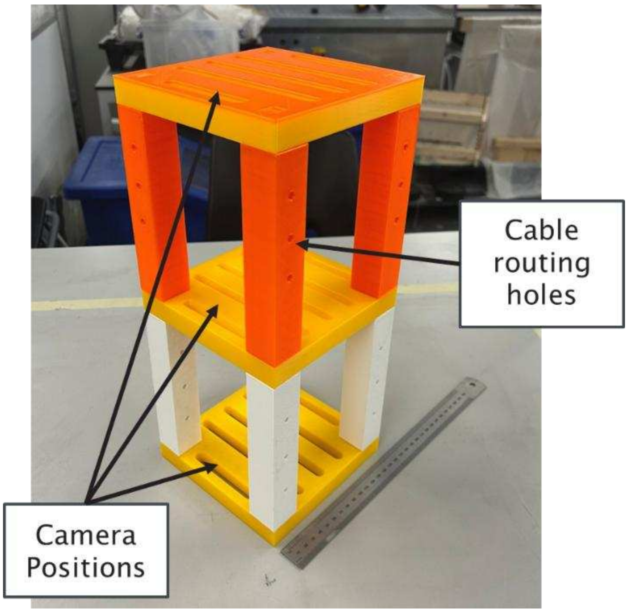

Figure 6. Camera support scaffold.

4 MODEL CONSTRUCTION

The primary type of soil model used for teaching is composed of soft clay, prepared from pre-consolidated blocks. Preparation of these soil models by the students involves the following steps:

(1) Soft clay is prepared by consolidation from slurry in split cylinder moulds. After consolidation, the clay is removed from the mould and sliced into discs, slightly greater than 75 mm in thickness, to suit the depth of the miniature strongboxes.
(2) Students are presented with a disc of soft clay, and a closed cutter of 3D printed plastic with an internal width that matches of the internal width of the mini strongbox. The top profile of the cutter varies depending on the soil model assigned to the student. Examples of these cutters, for different profiles of soil surface slope, are shown in Figure 7.
(3) The cutter is used to cut a sample from the block of clay. This is achieved by lubricating the inner faces of the cutter and then pressing it fully into the flat face of the clay, before removing the surrounding clay. The discarded clay is available for index testing and moisture content measurements by the students.
(4) The sample is trimmed using cheese wire to ensure the clay is flush with the front and back of the cutter.
(5) The clay model is then extruded into a miniature strongbox that is fully assembled except for the front window. 3D printed plungers that match the internal dimensions of each cutter are used to guide the extrusion.
(6) If desired, for easier visualisation of the soil deformation, the front face of the clay is marked using stencilled grid lines or a high contrast material. Dyed sand or coloured plastic powder is used, with the aim of matching levels of seeding density that are provided as examples (Stanier & White 2013).
(7) Finally, the front window is attached to the strongbox, and the model is ready for testing. An example model, prior to testing, is shown in Figure 8.

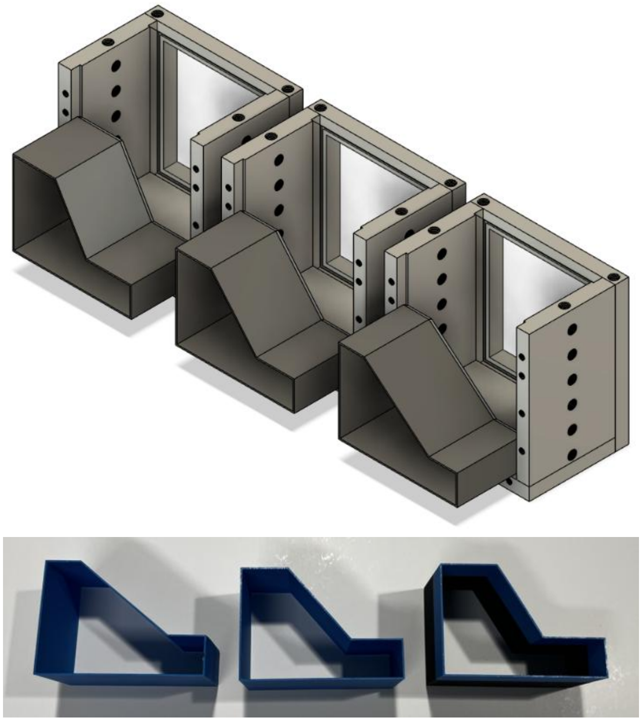

Figure 7. Pre-shaped model cutters – CAD and photograph.

Figure 8. Example of completed soil model ready to test.

5 PREDICTION OF TEST FAILURES

A range of soil surface profiles and model elements can be combined to create different geotechnical systems. To simplify the experimental arrangements to suit a teaching session, all of the models are subject to failure with increasing g-level. This approach eliminates the need for actuation and favours undrained testing of clay, rather than sand.

Slope stability tests have been widely performed using gravity turn-on methods since the initial days of centrifuge modelling (e.g. Lyndon & Schofield 1970). Also, foundation bearing capacity tests, in which the foundation load comes from the self-weight of a block of material resting on the soil, can also be performed using gravity turn-on. These two cases can also be combined to form a foundation at the crest of a slope.

The use of nine separate miniature strongboxes allows each student team to have hands-on experience, but it also allows a range of models to be tested in the same session. This has the advantage that each student team must complete their own analysis, using different parameters, to make an independent prediction of the g-level at which their own model will fail.

Using this approach, a set of nine models can be assembled using three slope angles with light and heavy foundations at the crest (or no foundation).

Predictions of the g-level at failure for the slope alone can be made using conventional textbook methods for undrained materials such as Taylor's stability charts (e.g. from Powrie 2014). For the foundation-slope interaction case the predictions can be made using simple design charts or upper bound solutions (e.g. Georgiadis (2010a and 2010b)).

The predicted failure g-level for an example set of nine models is shown in Figure 9. This set comprises three slope angles, β, and light and heavy foundations (or no foundation). The failure g-levels range from 28 to 94, ensuring continuous excitement and regular failures as the centrifuge is slowly accelerated.

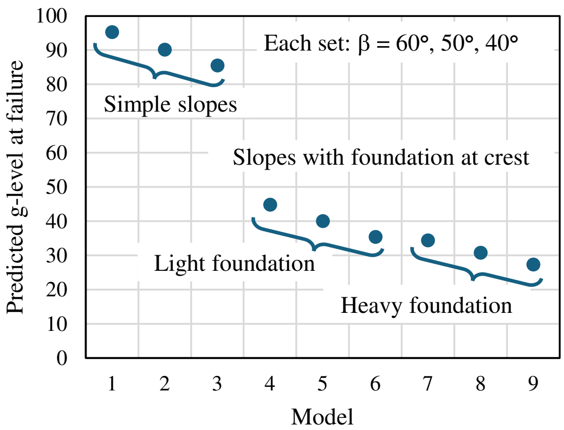

Figure 9. Predicted failure g-levels for nine model types.

6 CONCLUSIONS

A set of apparatus and experimental procedures to support centrifuge experiments in an undergraduate Civil Engineering program is described.

The apparatus is highly modular and easily handled by students, to maximise the efficiency and the 'hands-on' experience. The stackable miniature strongboxes permit up to nine samples to be tested concurrently, to fit a set of gravity turn-on tests in a timetabled lab.

The models are efficiently constructed using templates with different surface profiles. Students see a range of geotechnical system failures during a single laboratory session. During the associated coursework the students interpret the results using stability prediction methods from lectures, strengthening their understanding of the underlying analysis methods.

Also, the students gain hands-on experience of soil behaviour and benefit from the cohort-building and peer-to-peer learning aspects of group lab work.

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