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Centrifuge modelling of 3D energy wall systems embedded in unsaturated soil

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ABSTRACT: In alignment with the global effort in decarbonisation, energy geostructures are gaining increased attention due to the renewable and stable nature of geothermal energy. Heating accounts for the majority of energy consumption in buildings in temperate climates and cooling (air conditioning) is similarly demanding in tropical climates. While there has been significant attention on geothermal piles, studies of energy walls remain limited. This paper will describe the development of novel physical modelling techniques to create reduced-scale (1:25) ground energy diaphragm wall panels that can be used to form an enclosed basement. A model concrete with representative thermo-mechanical properties is used, combined with 3D-printed steel reinforcement cages and embedded silicone pipework. Specifically, the physical models are developed based on a field energy diaphragm wall system recently constructed in São Carlos, Brazil. Additionally, this paper will detail the process of developing a centrifuge model soil representative of a tropical unsaturated soil at the site. This research will provide a modelling approach that provides valuable data to support the advancement of new design methodologies for optimised geothermal solutions in challenging ground conditions, enabling future exploitation of energy walls.

1 INTRODUCTION

Nearly half of global energy consumption is associated with heating demand, but the exploitation of sustainable ground energy remains limited (REN21, 2024). In parallel, global warming is enhancing the need for cooling. Energy walls, which integrate ground source heat pump systems with retaining walls embedded in soils, are therefore increasingly promoted as a sustainable energy solution to support the goals of Net-Zero emissions.

Compared with other types of energy geostructures (e.g. energy piles/tunnels), studies on energy walls are limited, resulting in an insufficient understanding of the thermomechanical behaviour of such structures. This knowledge gap is particularly evident for complex configurations and soil conditions. Moreover, due to the scarcity of small-scale experimental data, validation of analytical and numerical models has typically relied on field data, which are costly to obtain and often site-specific.

As a cost-effective alternative to field testing, geotechnical centrifuge modelling enables extensive and systematic parametric studies using small-scale models in a well-controlled environment. Specifically, the study presented in this paper is part of the project: EPSRC-FAPESP Efficient ground energy systems in diaphragm walls in challenging conditions. The centrifuge models developed will be used for the validation of analytical tools developed at the University of Leeds (Gupta et al., 2025). Additionally, long-term heating and cooling processes can be simulated within significantly reduced time frames compared with full-scale field testing. Despite these advantages, the development of high-fidelity centrifuge models for energy walls is challenging due to the restricted space, instrumentation, and manufacturing feasibility of the components at reduced scale, particularly for 3D geometries. Existing studies on energy walls involving centrifuge modelling have primarily focused on plane-strain conditions (e.g., You et al., 2019; Minto, 2022), highlighting the need for further research on representative excavation geometries.

Building on the scaled reinforced concrete thermo-active wall panel presented in Guan et al. (2025), this paper details the novel techniques employed in the development of multi-panel basement geometries. The prototype in this study is a field basement constructed in Brazil, information on which can be found in Tosin et al. (2025a, 2025b). It was scaled to 1:25 (i.e. the scaling factor N is 25) after Schofield (1980) in the model development for testing at 25g at the centrifuge facilities of the University of Dundee. The scaling laws involved in this research are given in Table 1.

Table 1. Related centrifuge scaling laws in this research (after Schofield (1980), Taylor (2018), and Zhao et al. (2023)).

Parameter	Prototype	Model
Length	1	1/N
Stress	1	1
Strain	1	1
Force	1	$1/N^2$
Volume	1	$1/N^3$
Bending moment	1	$1/N^3$
Temperature	1	1
Thermal conductivity	1	1
Coefficient of thermal expansion	1	1
Time in heat convection	1	$1/N^2$
Heat flux	1	N

2 DEVELOPMENT OF MODEL SOIL IN ENERGY WALL SYSTEMS

2.1 Model soil selection

The soil selected for centrifuge testing is intended to represent tropical soil found in Brazil and be similar to that at the test site. Some characteristics of this soil are given in Table 2. The typical soil condition is unsaturated, meaning that soil suction, which is primarily controlled by the particle size distribution (PSD), must be considered carefully due to its influence on the mechanical behaviour of retaining walls. PSD and suction also affect soil thermal conductivity and consequently the heat exchange in energy wall systems. Therefore, the PSD of the field soil was adopted as the key characteristic that the model soil aimed to replicate. The soil properties in this section were obtained following BS EN ISO 17892 (BSI, 2016-2022).

Based on the approximate composition of the field soil, a series of mixtures was prepared using three commonly used model soil components: Kaolin clay, A50 silica flour (silt), and HST95 sand. The Atterberg limits of these mixed soils were measured, as listed in Table 3. Mixtures No. 2 and 3 show a better match in terms of both liquid limit and plastic limit compared with the others. Despite a slightly higher plasticity index, these two mixtures classify similarly to the field soil (low plasticity).

The PSDs of the soil components were measured using a Malvern Mastersizer 2000 laser diffraction analyser. Figure 1 shows the PSDs of these individual components, along with those of the soil samples taken from different depths at the field site. The field soil contains approximately 15% to 25% very fine particles with diameters smaller than 0.001 mm, indicating that a higher clay content is required for this study. Additionally, the field soil contains approximately 30% relatively coarse particles (particle size > ~0.2 mm), which are larger than those present in HST95 sand. Therefore, a portion of HST95 sand in the original soil mixture (No. 3) was replaced by HST50 (a coarser fraction).

Table 2. Characteristics of the study site soil in Brazil (from Machado, 1998).

Property	Value
Mineralogical composition quartz	~60%
Aluminium and iron oxides	~30%
Kaolinite and gibbsite	~10%
Liquid limit (LL)	22
Plastic limit (PL)	16
Plasticity index (PI)	6
Dry unit weight at the depth of 2 m	13.6 kN/m^3
Dry unit weight at the depth of 5 m	14.4 kN/m^3
Dry unit weight at the depth of 8 m	16.1 kN/m^3

Table 3. Atterberg limits of the various soil mixtures.

No.	Sand : silt : clay	LL	PL	PI
1	**60:10:30**	22.4	13.5	8.9
2	**60:15:25**	21.4	11.2	10.2
3	**65:5:30**	23.3	11.9	11.4
4	**65:10:25**	18.9	10.5	8.4
5	**65:15:20**	17.3	11.6	5.7
6	**70:15:15**	15.3	11.4	3.9
7	**75:0:25**	16.5	9.4	7.1

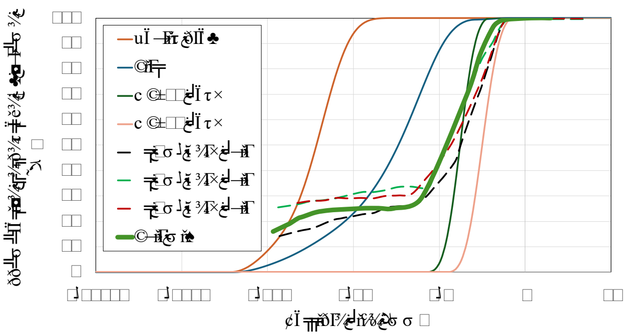


Figure 1. PSDs of field and model soil (field data from Machado, 1998).

The PSD of the resulting final mixture, comprising 30% HST50 sand, 35% HST95 sand, 5% silt, and 30% Kaolin clay, obtained using sieving and the hydrometer method, is also presented in Figure 1. The results show an amount of very fine particles smaller than ~0.001 mm towards the lower end of the expected range. As these particles may have a considerable influence on soil suction, Kaolin clay was replaced by Hymod AT clay which contains a higher portion of very fine particles (Robinson, 2019). The Atterberg limits of this revised soil mixture are summarised in Table 4.

Table 4. Model soil composition and Atterberg limits.

Constituent	Percentage	LL	PL	PI
Hymod AT clay	30%			
Silt	5%	23	11	12
HST95 sand	35%			
HST50 sand	30%			

2.2 Soil preparation

Standard Proctor compaction tests were conducted on the selected soil mixture as specified in BS 1377-2:2022 (BSI, 2022). As shown in Figure 2, the dry density of the model soil obtained is generally larger than that of the field soil (Table 2). Constrained by the liquid limit of the mixed soil, a water content of 22% was selected, resulting in a dry density matching the upper bound of the field values.

Due to the high clay content, pluviation followed by saturation was not suitable for preparing the model soil. An alternative preparation method for clayey soil was therefore trialled initially. The four dry soil components were mixed with water to achieve a water content of 36%. This mixture was poured into a rigid container with internal dimensions of 800 mm × 500 mm × 550 mm (length × width × height) and subsequently consolidated at 25 g in the centrifuge. However, consolidation was only partially achieved (U = 0.17) after 1.5 days of centrifuge spinning and was especially poor at shallow depths where the wall panels will be installed.

Given the ineffectiveness of in-flight consolidation, a compaction-based method was adopted as an alternative. This approach has previously been used for similar soil preparation by Sonnenberg (2008). The compaction energy was applied using a 2.5 kg rammer, as employed in the standard Proctor compaction tests. Preliminary trials were conducted based on compacting layer by layer in patches across the model. For each patch, a 10 mm-thick aluminium plate with dimensions of 155 mm × 125 mm (length × width) was used to apply 12 blows, distributing the compaction energy uniformly over the soil patch surface. Each soil patch was compacted until no further settlement was observed, with most settlement occurring within the first few blows. Based on these trials, a total of 12 blows will be used for actual testing, using the same rammer and a similarly sized plate. Figure 3 shows the soil texture after the compaction. The expected incremental thickness of each soil layer was achieved. These trials indicate that the compaction method is suitable for soil preparation in this study.

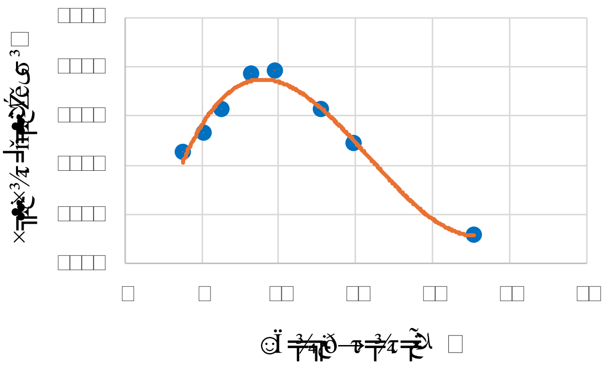


Figure 2. Compaction curve of the selected model soil mix.

Figure 3. A trial of the compaction method (plan view inside the trial box).

3 DEVELOPMENT OF ENERGY WALL MODELS

3.1 Design, instrumentation, and fabrication of energy wall panels

In this study, the 3D retaining wall system comprises 10 individual (diaphragm) wall panels. Figure 4 shows the dimensions of panel models. Each wall panel model is reinforced with a scaled steel cage that was 3D printed using stainless steel 316L at the Swiss Federal Laboratories for Materials Science and Technology (EMPA). The dimensions of these steel cages were obtained by directly scaling the dimensions of the field prototype by a factor of 1/25. Specifically, the scaled steel cages have dimensions of 140 mm in height, 60 mm in width, and 18 mm in thickness. However, such direct scaling resulted in very small model bar diameters (0.5 mm and 0.32

mm for longitudinal and transverse bars, respectively), which were too small to reliably resolve in the 3D printer. Therefore, a model diameter of 0.8 mm was adopted, as it can provide a good match in tensile strength with its reinforcement prototype (Elmorsy et al., 2024). To maintain the bending properties of the composite reinforced section, the number of steel bars was reduced to match the steel area in the field. Figure 5 shows the original and final design of the steel cage.

The heat exchanger pipe has an internal diameter of 14.5 mm, which corresponds to 0.58 mm at model scale following direct scaling. Flexible silicone pipes with an internal diameter of 0.5 mm were used in the model. Due to this small discrepancy in diameter, the pipework in the model was rearranged while maintaining the total (scaled) volume of water instantaneously within a panel, as shown in Figure 4. More information on the design and necessary modifications for these wall panel models can be found in Guan et al. (2025).

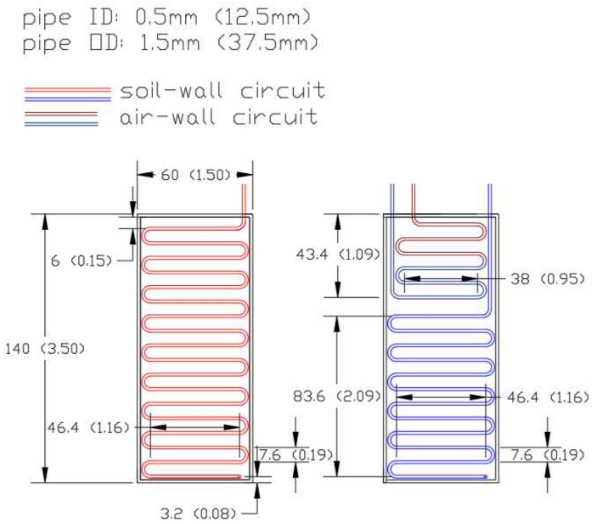


Figure 4. Details of a wall panel model (the model dimensions are in mm, with the corresponding prototype dimensions given inside the parentheses in m). (following Guan et al., 2025)

The wall panel models are instrumented with thermocouples and/or strain gauges. Due to space and hardware limitations, three different instrumentation schemes are adopted for different panels, exploiting symmetry, as shown in Figures 6 and 7. Three wall panels (T-1 panels) are instrumented with type K exposed junction thermocouples (TC) manufactured by RS Components on both sides, while four panels (T-2) are instrumented with two thermocouples on the soil side only (the first and the third counting down from the wall top). The thermocouples were coated with Plasti-Dip to protect them from water in the model concrete mix during casting. The coated thermocouples were tested against uncoated ones and the coating was observed to show a negligible effect on the response of the instruments to temperature changes. As shown in Figure 8, these waterproof thermocouples are tied to the reinforcing bars of the steel cages with thin wires.

The remaining three panels (M-T) follow the same thermocouple arrangement as the T-2 panels and are additionally instrumented with five full-bridge strain gauged locations (SG) to measure bending, as shown in Figure 7. These are 2-mm 350-Ohm linear GOBLET gauges with aluminium compensation (manufactured by Techni Measure) and are attached to an aluminium strip with a thickness of 0.8 mm. As the bending stiffness of this thin (dummy) plate is lower than that of the reinforced wall panel, it is expected to deform with the wall panel when positioned at the mid-thickness of the wall. Figure 8 shows the installation of strain gauges and thermocouples.

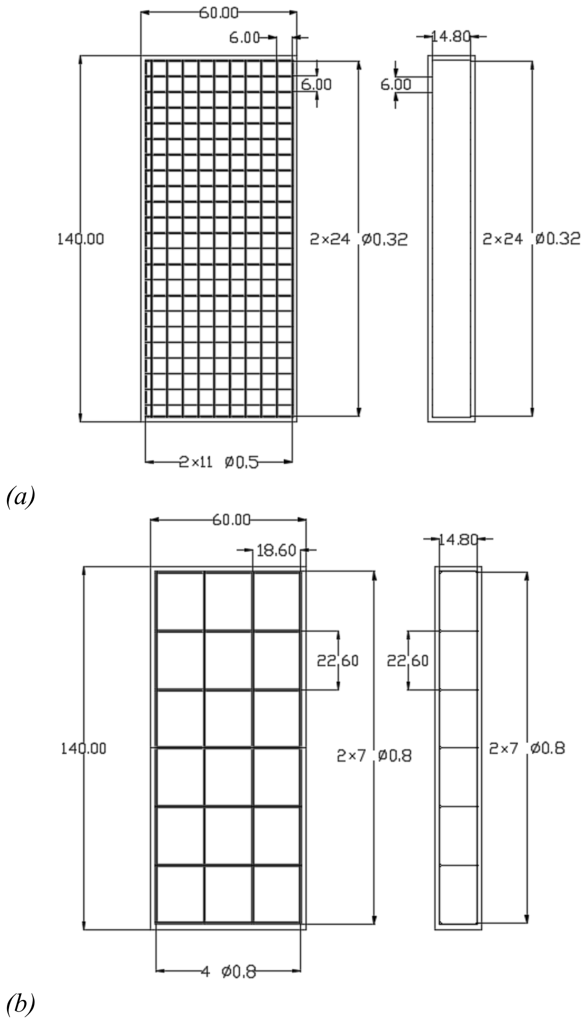


Figure 5. Reinforcement design (in mm): (a) direct scaling of the field design;(b) final model. (following Guan et al., 2025)

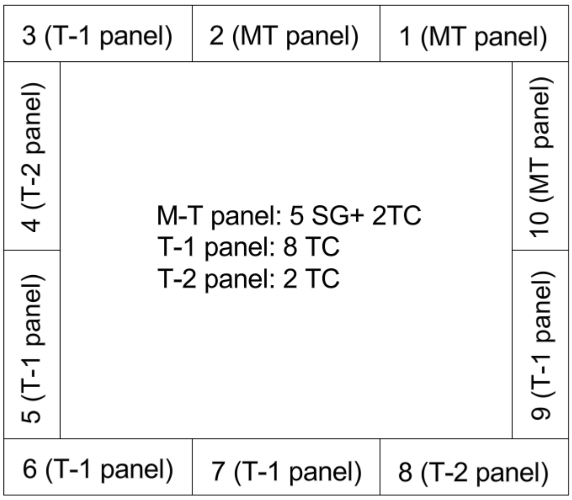


Figure 6. Schematic plan view showing instrumentation in the individual panels of the retaining wall systems.

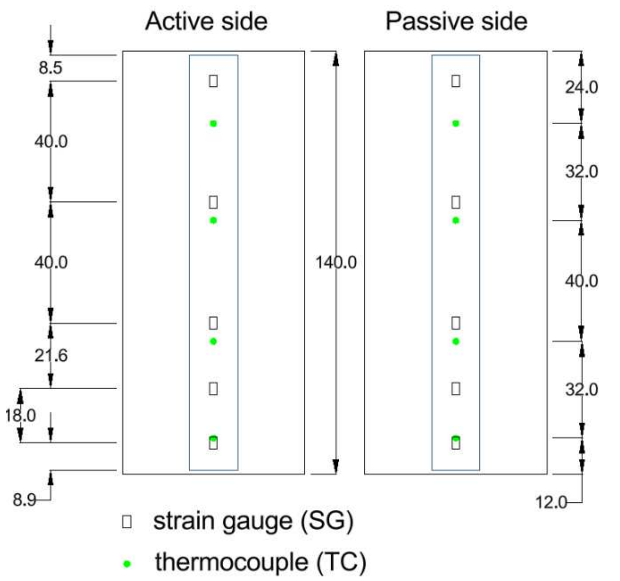
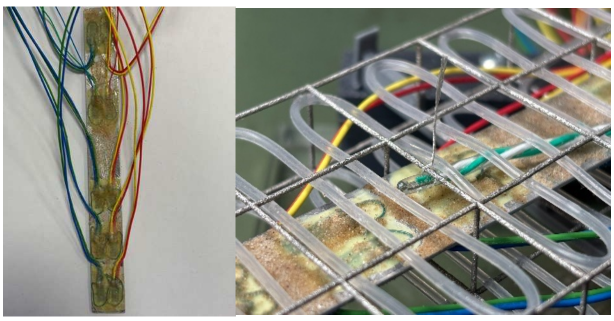


Figure 7. Schematic showing positions of instrumentation in a wall panel (all dimensions in mm).



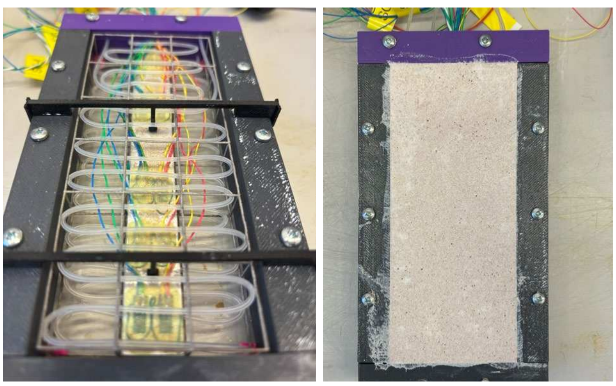
(a) (b)
Figure 8. Installing strain gauges and thermocouples inside the reinforcement cage:(a) strain gauges installed on a thin strip; (b) the strain gauge strip and a thermocouple tied to the steel cage.

The model concrete developed by Knappett et al. (2011) was used in this study. Its composition is listed in Table 5. The original model concrete has a much lower thermal conductivity compared with the field concrete. Thus, 6% copper powder (replacing part of the aggregate fraction) was added to increase thermal conductivity without significantly affecting its mechanical properties (Vitali et al., 2016). The water to plaster ratio (1:1) was selected for a suitably workable mix, resulting in a cylinder compressive strength of approximately 17.4 MPa (Knappett et al., 2011) which can be considered a reasonable representation of the C20 concrete used in the field.

Figure 9 shows the formwork used for model concrete casting. The steel cage and instruments were placed first. A cover depth of 1.6 mm was ensured using four small 3D printed supports placed at the corners of the steel cage. The strain gauge strip was held at mid-depth by two 3D printed suspension frames. The dry model concrete materials were mixed first, water was added, and the mixed model concrete was poured to approximately mid-depth of the formwork. This procedure was repeated to complete casting. This procedure ensured full contact between the steel cage, instrument strip, and the model concrete. This also allowed easy removal of the suspension frames once the aluminium strip had bonded with the surrounding concrete. Excess model concrete on the surface was smoothed. The cast wall panel models were demoulded after 24 hours and subsequently cured for at least 28 days. Finally, the wall panels were sprayed with silicone conformal coating for protection from soil and water, as they will be tested in unsaturated soil conditions.

Table 5. Composition of the model concrete used in this study (Percentage by Mass in the dry mix).

Plaster type	Plaster	HST95 sand	Copper powder	Water/ Plaster
β form	50 %	44 %	6 %	1



(a) (b)
Figure 9. Wall panel casting with instrumentation and flow pipes in place:(a) before casting; (b) after casting.

3.2 Wall panel installation

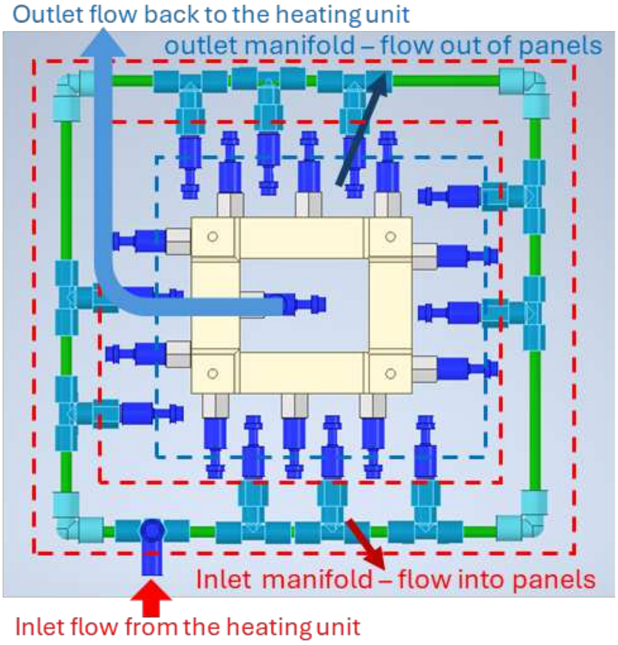
Excavation for wall panel models was trialled using the compacted soil in Figure 3. It showed that an unsupported vertical cut to a depth of 140 mm (i.e. the wall height) can be easily achieved. Thus, the retaining wall system will be installed after the soil preparation rather than during formation of the soil bed as the soil level increases.

4 DEVELOPMENT OF MANIFOLDS FOR ENERGY WALL SYSTEMS

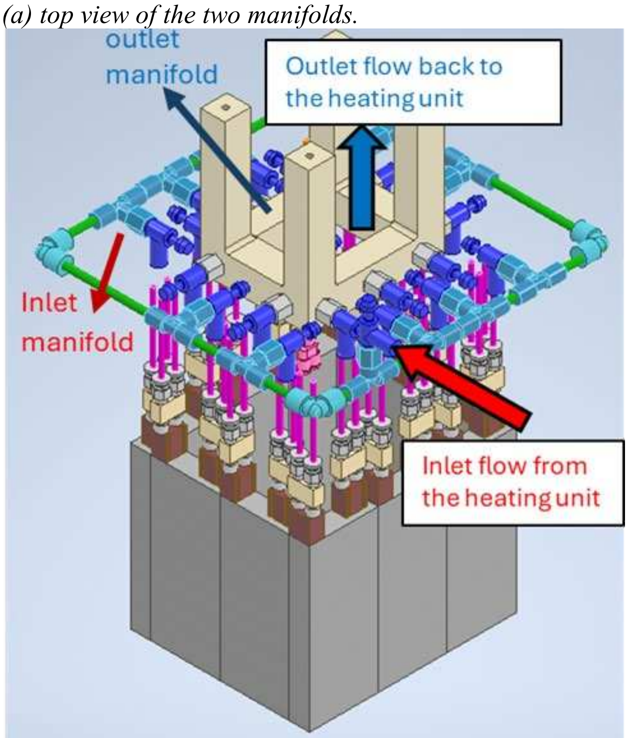
In the energy wall systems, two manifolds are required. One is for feeding the inlet water on each panel, and the other for collecting the outlets. Each port is connected to a flow controller to allow individual panels to be activated or deactivated as the test plan requires. Both manifolds are to be fixed to a support system at the same elevation above the wall system. As shown in Figure 10, the outer manifold is made using pipework and adaptors. The pipe has an internal diameter of 4 mm. Owing to space constraints, the inner manifold is manufactured using Stereolithography (SLA) 3D printing technology with Formlabs Grey Pro Resin, which provides a non-porous structure. Connections between the ports and flow controllers on the 3D-printed manifold are achieved by bonding threaded reduced bushes to the ports. This approach prevents cracking of the resin-based component (and subsequent leakage) that could otherwise occur due to excessive radial stresses generated when tightening the threaded connections.

5 CONCLUSIONS

This paper has described the development of a scaled 3D energy wall system embedded in unsaturated soil for centrifuge testing. The successful implementation of such a small-scale soil-structure system has provided useful guidance on techniques that can be applied to complex and sophisticated physical modelling. Specifically, 3D-printing techniques employing different principles and materials can be effectively utilised in centrifuge testing to meet specific experimental requirements. The development of a model soil representative of tropical soils also provides suggestions for replicating other field soils in physical modelling studies. In summary, this study establishes a practical methodology for the physical modelling of reinforced energy wall systems in unsaturated soils using centrifuge testing.



(a) top view of the two manifolds.



(b) the two manifolds in the energy wall system.

Figure 10. Illustrations of the two manifolds used in the energy wall system.

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