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Reduced-scale physical modelling of energy walls in partially saturated soils

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ABSTRACT: Energy geostructures are often designed assuming fully saturated or dry soil conditions, although their shallow depth frequently implies interaction with partially saturated soils. Under these conditions, soil thermal and hydraulic properties depend on moisture content, and temperature gradients induced by thermal operation may activate moisture migration, affecting heat transfer. Experimental evidence addressing these coupled thermo-hydraulic processes remains limited, particularly for energy walls. This paper presents a laboratory physical model of a reduced-scale energy wall embedded in partially saturated, uniform sand. The setup allows controlled investigation of heat exchange, temperature gradients, and moisture redistribution under imposed thermal loading. Soil thermal conductivity and hydraulic properties were characterized under unsaturated conditions to support test interpretation and future numerical modelling. Preliminary heating tests show expected temperature gradients with distance from the wall and time-dependent thermal response, while moisture variations appear very limited and delayed. A verification on the possible influence of soil–atmosphere interaction on moisture evolution at shallow depths is recommended. Although not intended to reproduce field-scale behaviour quantitatively, the model may provide benchmark data for validating coupled thermo-hydraulic numerical simulations and improving prediction of energy wall performance in partially saturated soils.

1 INTRODUCTION

The use of energy geostructures to harness the ground as a thermal energy reservoir is supported by decades of design experience and established modelling techniques (Brandl, 2006; Bourne-Webb et al., 2016; Sani et al., 2019). These models provide preliminary estimates of the geothermal potential and quantify expected energy exchange for various operating modes, as well as thermally induced stress-strain effects.

Predictive models are typically based on the assumption of either fully saturated or completely dry soil conditions, which simplifies the modelling of the coupled physical processes and the estimation of the soil's thermo-hydro-mechanical properties. However, due to the limited depth reached by energy geostructures, a substantial portion of the soil mass thermally involved is often in partially saturated conditions. In this case, the presence of air alters the soil properties and the overall thermal performance of the energy geostructure tends to reduce. Moreover, the geostructure operations induce in the soil mass thermal gradients that activate moisture migration, revealing the fully coupled thermo-hydraulic nature of the process (Philip and de Vries, 1957; Ewen and Thomas, 1989; Thomas and He, 1997).

The complexity of modelling energy geostructures in partially saturated conditions stems from two factors: (i) soil thermal and hydraulic properties vary according to the degree of saturation; (ii) thermal gradients caused by the energy geostructure operation induce moisture movements, which in turn alter thermal and hydraulic properties (e.g. Akrouch et al., 2016; Cherati and Ghasemi-Fare, 2019; Sani and Singh, 2020). In this context, two relevant questions rise, about quantifying the loss of performance in partially saturated soil conditions, as well as the significance of the thermo-hydraulic coupling. The controlled conditions of a laboratory setup allow for investigation of these aspects; however, while the energy pile typology has received the most attention (Faizal et al., 2021, Zeng et al., 2024), there are fewer examples of energy wall physical models, and none focused on investigating the effects of unsaturated soil conditions (Dong et al., 2019; Li et al., 2026).

A laboratory physical model of a reduced-scale energy wall was then designed to gain insights into two aspects: the influence of partial saturation on energy wall performance and the practical significance of moisture redistribution due to thermal gradients. The paper describes the physical model setup, the characterization of soil hydraulic and thermal properties under unsaturated conditions, and the results of preliminary tests carried out on uniform coarse soil.

2 PHYSICAL MODEL SETUP

The reduced-scale physical model of energy wall was designed adapting existing facilities at the Building Physics Lab, Department of Energy, Politecnico di Milano (Angelotti and Molinaroli, 2019). The aim was to simulate the energy wall thermal activation in a soil mass of controlled initial density and volumetric water content (VWC), and to assess heat exchange variations and induced temperature gradients and moisture migration.

2.1 Sand box structure and dimensions

The set up consists of a wooden reinforced PMMA box (base area equal to 120 cm x 60 cm, filled height equal to 80 cm), internally equipped with two lateral reservoirs, separated by perforated steel plates covered with geotextiles, which are used to introduce a groundwater table and possibly a crossing water flow (Figure 1). The reduced-scale energy wall, made of concrete, is fully embedded in the mid-section of the box and has width, height and thickness respectively equal to 60 cm, 40 cm and 5 cm. The energy wall includes two heat exchanger pipes, with internal and external diameters of 5 and 10 mm respectively, fastened to a reinforcing steel bar grid (Figure 2).

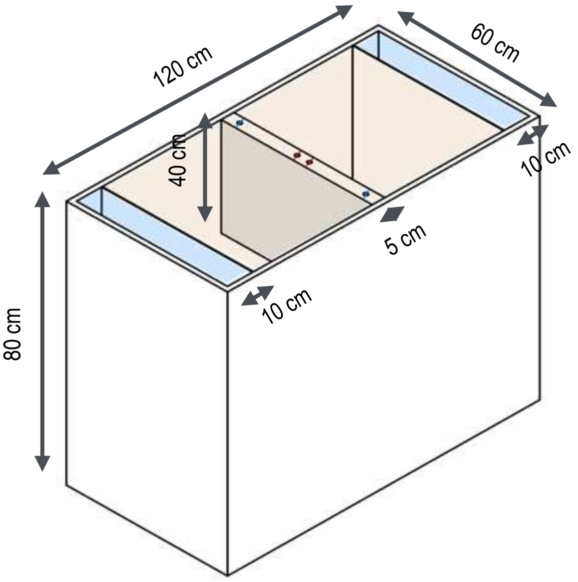

Figure 1. Schematic view and dimensions of the laboratory sand box with mid placed model of energy wall.

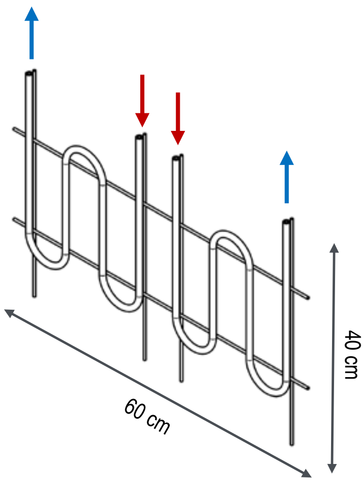

Figure 2. Detail of the steel bar grid and two heat exchangers embedded in the energy wall.

The system is completed with a hydraulic circuit, devised to circulate water in the heat exchangers and comprising a peristaltic pump (Kamoer DIPump KPK400) and a thermostatic water bath (Elettrofor, M405-BO), which control the fluid flow rate and the inlet temperature, respectively.

2.2 Sensors and data acquisition

The apparatus is equipped with ground embedded sensors at various depths and distances from the energy wall face: 24 T-type thermocouples and 6 Frequency Domain Reflectometry (FDR) probes (METER EC-5, VWC range 0-100%, ±2% accuracy after soil specific calibration) for the continuous monitoring of temperature and VWC distribution. In addition, 10 thermocouples embedded in the concrete wall monitor its temperature variations, both near the face and in the heat exchangers mid section.

Heat exchange rate is quantified throughout the test, via the continuous measurement of inlet and outlet water temperatures and flow rate, respectively obtained with additional thermocouples inserted in the hydraulic circuit and a flowmeter (ZHM 01/3 Gear flowmeter, volumetric flow rate range 0.002 – 0.5 l/min, accuracy ±2%).

The data acquisition system is composed of an 8 slots compact chassis NI C-DAQ 9174 equipped with modules dedicated to thermocouples acquisition (NI 9214) and DC Voltage/Current acquisition (NI 9207).

Thermocouples were calibrated in a thermostatic water bath in the range +10÷50 °C, while FDR sensors were calibrated embedding them in compacted soil samples reconstituted at known values of VWC in the range 0÷32%, corresponding to the saturation range 0÷75%. Moreover, while thermocouples provide a spot measurement, FDR sensors require preliminary evaluation of sampling volume around the prongs, estimated as a cylinder of approximately 45 cm^3 (Sheng et al., 2024), and of possible interference with nearby metal elements. The alternative option of using miniaturized tensiometers for the indirect spot assessment of water content, by way of the soil-water retention curve, was abandoned due to the need to guarantee high accuracy on a low suction range.

2.3 Test procedure

The box is filled with sand in layers of about 10 cm height, using the moist tamping technique which ensures uniform target density and moisture. For each layer, the prescribed dry soil mass and water mass are hand mixed, poured and compacted with a manual hammer until the layer's height, marked with rulers fixed on the box walls, is reached. The concrete energy wall lays on two side supports, because the low compacted sand mass does not provide sufficient load bearing capacity. During the filling process the probes are placed at prescribed heights and distances from the energy wall, paying attention that further compaction does not damage or displace them (Figure 3). The positions of FDR probes are selected considering their sampling volume, to avoid interference with each other and with thermocouples. The investigated depths from soil surface and distances from energy wall face are 12, 28, 40, 52 cm, and 5, 10, 20 cm, respectively. In addition, two points at the soil surface and one point at the box bottom were monitored as reference values.

After the energy wall is placed the filling procedure is completed on the two wall's sides. At the end, a plastic sheet is laid out on the sand surface to prevent moisture migration to/from the room and the hydraulic circuit is connected (Figure 4). An overall view of the sand box is shown in Figure 5.

Tests are designed to simulate heating, with constant inlet fluid temperature and mass flow rate, and following free-floating phase; the heat flow exchanged by the energy wall is expected to depend on the soil moisture conditions. The lateral reservoirs can be filled with water up to target heights, to reproduce conditions of hydrostatic groundwater table or seepage regime with controlled hydraulic gradient.

3 MATERIALS AND PROPERTIES

The sand used in the tests is 80% silica, with specific gravity of 2.75, D_{50} of 0.28 mm and 2.2 as uniformity coefficient. The tests were performed with sand compaction at a relative density of 50%.

In the prospect of a test simulation by thermo-hydraulic coupled modelling, the assessment of thermal and hydraulic properties at the prescribed compaction is necessary.

Figure 3. Exact placement of FDR probe with the aid of a plumb line and sand compaction with manual hammer. Wooden benches for the energy wall support are visible along the box sides.

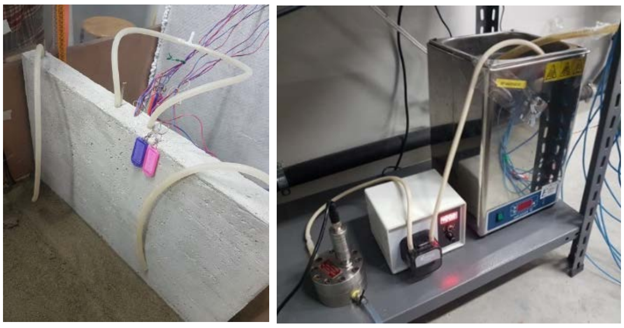

Figure 4. Concrete energy wall with in and out pairs of heat exchanger pipes before complete box filling and hydraulic circuit controllers (thermostatic water bath, peristaltic pump and flowmeter).

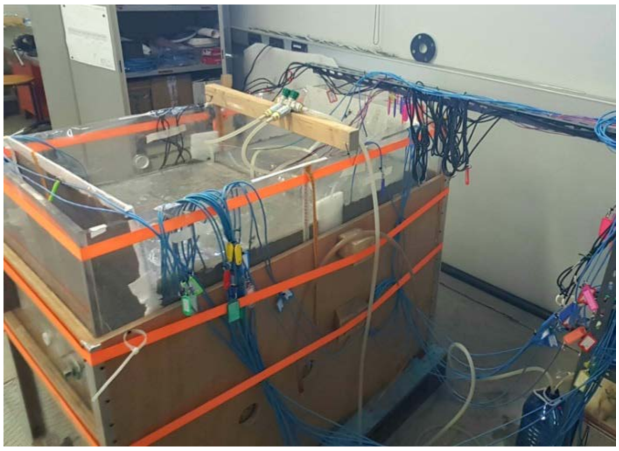

Figure 5. Overall view of the physical model setup.

A Hot Disk thermal constant analyser based on the Transient Plane Source method was used to estimate the soil thermal conductivity at different VWC from dry to saturated conditions, obtaining minimum and maximum values of (0.232 ±0.005) W/(m·K) and (1.84 ±0.01) W/(m·K), respectively. The relation between soil thermal conductivity and VWC was interpreted with an optimized non-linear Coté-Konrad model (Coté and Konrad, 2005). The soil water retention curve was estimated using a volumetric pressure plate extractor apparatus and interpreted with Mualem-van Genuchten model in the range of 0.5÷11 kPa. The permeability function was modelled based on the estimated soil water retention curve (van Genuchten, 1980). Air entry value and residual suction were estimated equal to 1.85 and 4.55 kPa, respectively.

4 PRELIMINARY TESTS

The preliminary tests aimed to verify the adequacy of the laboratory setup and testing procedure and to estimate the order of magnitude of the variables involved and their variations. In particular, a main concern was the possibility to obtain substantial moisture-dependent heat exchange values and measurable VWC variations.

4.1 Testing condition

The tests were carried out with a sand relative density of 50%, corresponding to a void ratio of 0.73, and a design VWC equal to 10%, corresponding to a degree of saturation of 23.6%. The resulting moist density is 1.68 g/cm^3. A total weight of about 720 kg of sand and 45 kg of water were employed.

The estimated void ratio profile, up to the depth of interest (52 cm), was in the range 0.727÷0.753, indicating an acceptable uniformity of sand density. At initial conditions the monitored wall and soil temperatures were equal to the room temperature of about 23°C, as daily average, while VWC ranged between 6% and 10% depending on the depth. This reveals the difficulty in preventing natural soil moisture loss during the long procedure of sand box filling, especially in warm and dry rooms.

The lateral reservoirs were left empty, to reproduce a condition where the water table is very deep in the ground with respect to the energy wall depth and no groundwater flow is present.

The first tests were run with temperature set-points of the thermostatic bath in the range 33÷43°C, i.e. +10÷20°C with respect to the room temperature, and a constant flow rate of 0.264 ml/min (average value, with standard deviation of 0.002 l/min), corresponding to an average fluid velocity of 0.224 m/s. Considering the temperature dependent properties of water, the Reynolds numbers were in the range 1488÷1862, thus indicating laminar flow. The heating phase lasted 4 to 7 hours, followed by a free-floating time of 2 to 4 days.

4.2 Test results and discussion

As an example of test results, some trends from the test where the temperature set-point was 33 °C are reported. Figure 6 shows that, after a transient initial phase of about 3 hours, the fluid inlet temperature approaches almost steadily 31 °C, but the heat transfer rate continues to decrease due to a slight gradual increase of the outlet temperature. This effect is the result of the transient heating of the concrete wall. The average temperature difference of the fluid between inlet and outlet was 2.0 °C and the average heat rate was 36 W, corresponding to a specific heat rate of 151 W/m^2 per energy wall unit surface or 71 W/m^2 per unit soil-wall interface area. These values should not be straightforwardly compared to the expected energy performance of full-scale energy walls, given the limits of the physical model scale reduction.

Figure 7 shows the temperature variations, 12 cm from the soil surface on the median plane of one of the heat exchanger loops, at different distances from the wall face. As expected, the thermal response was almost immediate at the wall face, while the time lag increased the further the probe from the face. At the end of the test the temperature increased by 3.4 °C at the wall face and by 0.7 °C at 20 cm.

While temperature variations were easily detected, FDR probes reported almost negligible changes of VWC: Figures 8 shows that at 5 and 15 cm distances from the energy wall face even the largest VWC variations, with respect to the initial value, are lower than 0.4% all along the test duration.

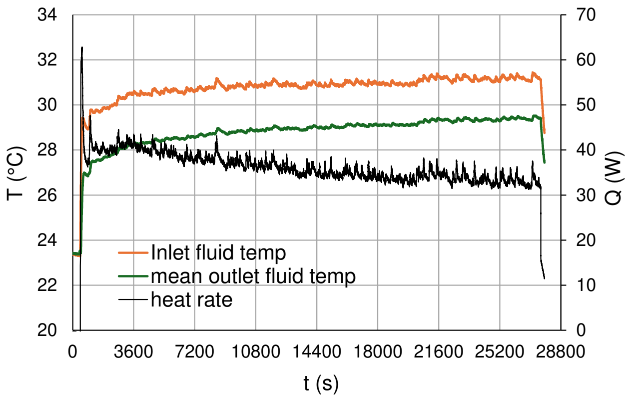

Figure 6. Performance test: inlet and outlet fluid temperature and exchanged heat rate versus time.

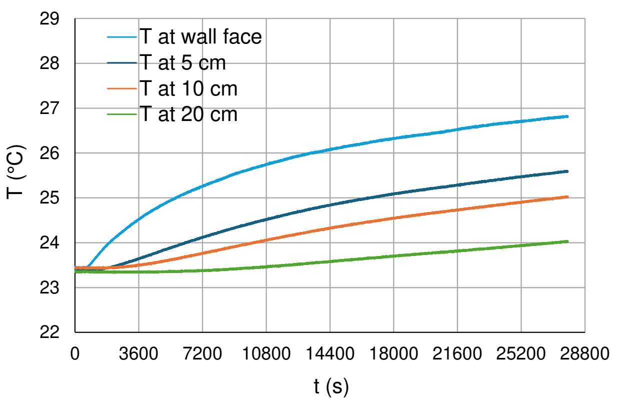

Figure 7. Performance test: soil temperature at 12 cm depth and different distances from the energy wall face versus time.

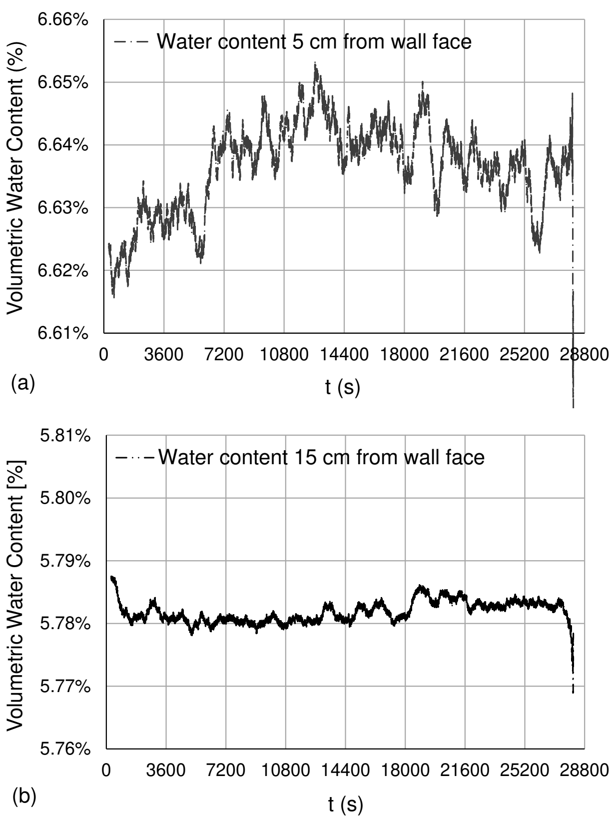

Figure 8. Performance test: volumetric water content at 12 cm depth versus time, at 5 cm (a) and 15 cm (b) distance from the energy wall face.

Assuming that the VWC measurement can be considered reliable at close distance from the energy wall (5 cm), an explanation for trend observed in Figure 8.a is provided in the following. Theoretically, a local temperature increase enables water to move away towards cooler positions, i.e. the origin of water migration is the temperature gradient. When the temperature profile along the distance from the wall shows a gradient, as in the transient case of a heat source, each point receives water from warmer positions (closer to the source) and releases water to cooler positions (further from the source), in a continuos unbalance between entering and leaving fluxes. In the test, although the temperature at 5 cm distance is monotonically increasing (Figure 7), the VWC at the same distance increases as well, up to 3.5 hours after the test start (Figure 8.a), likely because the entering water flux from nearby warmer points is still greater than the leaving water flux towards nearby cooler points. After 3.5 hours, the temperature gradients have changed so that the water mass balance is inverted: the flux from warmer points becomes less than the flux to cooler points, thus inverting the VWC trend as well. The resulting apparent inconsistency between local temperature and VWC trends, i.e. a temperature increase locally associated with a VWC increase, is therefore explained as a natural time lag in the measurement of the net VWC change.

In general, the same results were observed in all the preliminary tests. It should be also noted that VWC variations may not be uniquely linked to the energy wall activation. Further investigations are necessary to distinguish moisture variations possibly induced by the heating experiments from the baseline variations related to water vapour exchange between the laboratory room and the soil mass, especially at shallow depth. The monitoring of room temperature and humidity during the test would aid in this verification.

Coupled hydro-thermal numerical simulations of the reduced scale physical model, performed to aid in the optimal design of the laboratory apparatus, confirmed marginal moisture migration and its dependence on heating magnitude and duration, with evident time lag effects (Presutto, 2025).

Limited moisture migration is in any case expected in these tests, unless high thermal gradients are maintained for long time durations. Faizal et al. (2021), report that heating a model energy pile at 36 °C (15 °C above room temperature) induces, at 5 cm distance after 1.5 days, a temperature change of 7 °C and a VWC increase from 6.1% to 6.3%. If this temperature condition is maintained, the VWC trend then inverts until a final VWC value of 4% is reached 10 days after the heating start.

Higher temperatures and longer durations were considered also by Behbehani and McCartney (2022), investigating the use of energy pile groups in a silty soil for heat storage applications. After validation based on physical model tests, they performed numerical analyses with inlet fluid temperatures cycling between 30°C (simulating heat extraction phase for 6 months) and 90°C (injection phase for 6 months). The results show that, at points where the soil temperature yearly varies in the range 10÷62°C, the reduction of the degree of saturation is in the range 1÷10%, from the initial value of about 25%.

The water migration effect could be enhanced also with different initial moisture values, as observed by Başer et al. (2018). When establishing initial soil moisture conditions in the physical tests, an ideal compromise should be found between values that ensure easy and effective sand compaction and values that promote water migration.

The use of finer materials, such as unsaturated silt, reveals different thermally induced water migration effects and opens addition perspectives in the context of bearing capacity and thermo-mechanical behaviour of energy geostructures (Goode III and McCartney, 2015, Bodas Freitas et al., 2021).

5 CONCLUSIONS

The newly designed laboratory physical model of a reduced scale energy wall proved to be a promising tool to investigate the effect of soil partial saturation on the heat exchange and the significance of the coupled hydro-thermal processes, namely the water migration under thermal gradients. From a technical point of view, the possibility to use alternative sensors for volume water content measurement is currently under investigation.

The preliminary tests reported the occurrence of expected temperature gradients with distance from the heat source and temperature variations with time. The moisture changes show a time lag with respect to temperature variations and are hardly detected if heating is not maintained for a sufficiently long duration. High temperature values at the circuit inlet could enhance moisture changes as well.

The soil-atmosphere interaction should be carefully considered, as its contribution to moisture variation through vapour exchange may be not negligible with respect to thermally induced effects, especially at shallow depths. Soil moisture variations due to vapour exchange are expected also during the long procedure of sand layers deposition.

The reduced-scale tests were not intended to quantitatively represent the response of a field-scale energy wall. However, the setup allows to collect the necessary temperature and water content data for a comparison with the outputs of numerical simulations, thus enabling the validation and calibration of a numerical model which can be used as a predictive tool, aiding design and optimization of energy geostructures. Specifically, the direct experimental assessment may confirm or deny the need to include thermo-hydraulic full coupling, in contrast to the simplified form which neglects water content variations induced by temperature gradients. Moreover, extensive testing with different soil moisture distributions (and possible groundwater seepage) will provide indications about thermal performance losses (or gains).

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