Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Study of thermally active piles for climatization of structures in tropical soil

Etude des pieux thermiquement actifs pour la climatisation de structures en sol tropical

Juan C. Silva & Renato P. Cunha
Department of Civil and Env. Engineering, University of Brasília, Brazil, rpcunha@unb.br

Charles Chaves
Department of Civil Engineering, Federal Institute Goiano, Brazil

ABSTRACT: This paper provides preliminary results on geothermal energy piles (GEPs) for the thermal climatization of structures founded on the typical tropical unsaturated soil of the central region of Brazil. The research employed a series of prototype simulations of a thermal pile embedded into a calibration chamber with compacted unsaturated soil. It closely simulates the behavior of a (prototype) section from real scale GEPs founded in the geotechnical media of the region, in terms of compactness, mineralogy, water content and thermal variables. One of the on-going thermal tests was numerically simulated with a multiphysics commercial software, so to calibrate a model and to expand the results to possible scenarios of distinct (laboratory) GEP performance. The analyses will base future simulations of typical foundation layouts for large-scale structures founded on tropical soils of the region, so to verify the thermal energy efficiency under average operational conditions. Besides of the known limitations of this research, still at early stage, an initial assessment was achieved for the design of shallow geothermal systems for local conditions.

RÉSUMÉ: Cet article fournit des résultats préliminaires sur les pieux géothermiques (GEP) pour la climatisation thermique des structures fondées sur le sol tropical insaturé typique de la région centrale du Brésil. La recherche a utilisé une série de simulations de prototypes d'une section de pieu thermique intégrée dans une chambre d'étalonnage avec un sol non saturé compacté. Il simule étroitement le comportement d'une coupe à partir de GEP à échelle réelle intégrés dans les milieux géotechniques de la région, en termes de compacité, de minéralogie, de teneur en eau et de variables thermiques. L'un des tests thermiques en cours a été simulé numériquement avec un logiciel commercial multiphysique, afin de calibrer un modèle et d'étendre les résultats à des scénarios possibles de performance de GEP sur le terrain, soit en isolat, soit en groupe. Un plan de fondation possible pour un silo avec des pieux forés a été vérifié par rapport à différentes variables externes, afin de vérifier le flux de chaleur dérivé dans des conditions de fonctionnement (suffisamment proches). Outre les limites connues de cette recherche, encore à un stade précoce, une évaluation initiale a été réalisée pour la conception de systèmes géothermiques peu profonds pour les structures agro-industrielles locales.

KEYWORDS: tropical soil, energy pile, calibration chamber, numerical simulation, sustainable energy.

1 INTRODUCTION

Greenhouse gas emissions produced by fossil fuels are causing a slow change of the climate´s conditions. Air conditioning systems in superstructures demand a considerably amount of the existing carbon related energy sources, which are non-renewable. In this regard many developed countries have addressed Shallow Geothermal Energy (SGE) as a renewable source of energy worthy of investment and development. SGE refers to the exploitable thermal energy in the shallow subsurface of the earth, using ground source heat pumps to exchange ground heat and provide sustainable energy to superstructures. These energy systems can provide cooling to buildings, helping the reduction of harmful gas emissions (Brandl 2006). They can be also useful to agro-industrial structures, possibly to be employed in grain silos, storage rooms, animal sheds, and other living or working structures largely present within Brazil´s Midwest agribusiness frontier.

In this industry, for instance, storage silos or barns must be refrigerated to keep crops from germination or deterioration processes, being mostly used during harvesting season. Other structures must also be refrigerated, so to store seeds, fertilizers, farming equipment, animals, as well as living residential quarters. Feasibility of SGE usage for the region has not yet been assessed, but in order to provide a sustainable solution one must initially understand its potential to be implemented into local conditions, and know how to design it to provide heat loads that are usually demanded by common/existing structures.

Hence, this paper focus on the potential use of energy piles to climatize silos, barns, or agricultural deposits, through the exchange of heat with the typical, all around, mostly unsaturated tropical soil of the Brazilian Midwest region (Figure 1). The agribusiness in this central region is strong and it competes in a worldwide range, which would allow the implementation of clean sustainable energy systems that are uncommon in Brazil, and also are relatively expensive to implement given the lack of companies, technology, personnel and expertise.

As most of the needed energy is supplied from the ground, the SGE system contributes to the cost saving operation of the superstructure, besides of decreasing the release of greenhouse gases to atmosphere (a critique which is made to large-scale meat producer farms of the Brazilian Midwest).

Nevertheless, there are certain minimum requirements for the installation of SGE systems, as an abundant array of previous publications has already ascertained in the literature, especially in the last 5 years or so (for instance, Akrouch et al. 2015, Di Donna et al. 2016, Olgun et al. 2017, Salciarini et al. 2017, Rotta Loria et al. 2018, Sani et al. 2019, Sani et al. 2020 and Bourne-Webb & Bodas Freitas, 2020).

Unsaturated soils are also rarely considered as thermal medium for heat exchange, although experience has shown that the SGE system works, besides of a decrease in heat exchange efficiency (Ahmadipur and Basu 2016, Akrouch et al. 2016, Sani et al. 2018). It seems, however, that the typical laterized tropical soils of the Midwest region of Brazil have special features that may render them more feasible for SGE exploitation, as an abundant presence of iron and aluminum oxides. This mineralogical characteristic, from pedogenetic aspects of their formation, do increase their overall thermal conductivity (Bandeira Neto 2015, Orozco 2016, Sousa Júnior 2017). Of course, this poses an extra challenge to the design but nevertheless encourages further research in this direction.

Efficiency in SGE systems also depends on other variables. For instance, stable ground temperature over seasons is inevitable for sustainable long-term heat exchange operations. A geothermal heat exchange system is considered balanced, when the heating and cooling demand is approximately the same. When the heating or cooling demand is greater than the other, there is a nonsymmetrical energy expense, and the whole system becomes unbalanced. Generally speaking, in the majority of the Brazilian regions, the operation of ground source heat pump (GSHP) systems would be unbalanced, as the cooling demand is higher than the heating one, throughout the year. Thus, the geotechnical medium can gradually heat up and loose efficiency for thermal storage. In case of GEPs the increase in axial stress and strain is observed (Akrouch et al. 2014, Murphy et al. 2015, Abdelaziz and Ozudogru, 2016). This phenomenon can be explained by the difference in the thermal expansion coefficients of the pile and the soil, and end restraints, as well demonstrated by Goode and McCartney 2015. This is certainly another challenge for design.

Therefore, before full application within local geotechnical, environmental and thermal constraints, a research must be done to understand how SGE systems can operate on a daily basis, either at short and large time frames, considering the existing unsaturated medium and local temperatures. So, with prototype tests that simulated a GEP section immersed into a compacted soil "representative" of the region, and thermal variables derived from both lab. tests and empirical correlations, it was possible to gather information on a "normal" GEP operation that served to calibrate a thermal model for subsequent numerical simulations.

Distinct working scenarios for heat flow production by an isolated energy pile were numerically evaluated by a multiphysics commercial software, considering several external variables as flow, fluid inlet temperatures and pipe configurations. Steady state conditions were assumed in the parametrization, with distinct time frames of heat production.

The exercise proved to be of value to grasp an initial understanding on potential capabilities for exploiting thermally active piles into local structures. It has shown to be theoretically feasible, experimentally valid, and possibly operational as well, although further validation is mandatory to broaden the knowledge to real scale & time conditions.

Energy demand in the region is surely existent, and the sustainable appeal is strong, but implementation of this technology still depend on other factors, yet to be matured, as availability of technology, design companies and contractors, governmental policies & funding, public awareness, and experimental large-scale research. Actually, lots of research.

Figure 1. Brazilian states and Midwest region: The agribusiness frontier for exportation of commodities (modified after Wikipedia 2020).

2 EXPERIMENTAL STUDIES

2.1 *Thermal tests in calibration chamber*

In order to calibrate the numerical model and to understand the behavior of the GEP prototype under heat exchange conditions an initial setup test was performed inside a thermally insulated chamber (as shown in Figure 2). The dimensions of this cylindrical chamber were 1.1 m in diameter by ~1 m in height.

The developed prototype of the geothermal pile was 1m long and 20 cm in diameter, with internal PEAD exchanger tubes of ¾ inches in external diameter into an overall 4U loop configuration. This allows heat exchange tests with U, 2U and 4U layouts, so expanding the experimental possibilities. The tubes were uniformly distributed along the steel reinforcement cage of the GEP, and thermo sensors were installed at distinct compacted layers surrounding the pile so to check the all-around temperature, and those dissipated along the chamber radius, at distinct points in the compacted layers (see Figure 3).

The prototype was executed and concreted in a compacted soil within the chamber with average humidity of 20%, void ratio of 0.8, porosity of 44% and dry unit weight of 13.6 kN/m^3. The soil was compacted into 12 sequential layers so to approximately simulate "average" conditions of the tropical laterized soil of the Federal District of Brazil, where the Univ. of Brasília geotechnical research site is located (home base of the studies presented here).

The compaction process was carried out by layering with a manual compactor with a 16 x 16 cm square socket, weight of 10.73 kg, drop height of 27.5 cm, and 513 strokes per layer, evenly distributed over the 12 soil layers. This procedure has enabled a total compaction energy of approximately 24 kgf.cm/cm^3. These specifications allowed the compacted specific weight, density and other soil variables to "approach" those conditions found in the field deposit, normally derived via previous lab. data and parameters estimated by traditional SPT correlations at this site. The chosen humidity was the lower possible in the dry range of the curve that permitted the desired dry unit weight with a homogeneous compaction.

Figure 4(a) presents the initial results from inlet and outlet temperatures for the 4U configuration in which a (200 h) test program with a fluid flow of 15 l/min and an inlet temp. T_{in} of 61°C was adopted. This temperature justifies a possible thermal expansion of the GEP when used into an industrial application. Further tests at other conditions are expected soon. Figure 4(b) complements the previous figure presenting temperature dissipation profiles around the pile shaft surface and at distinct radial distances around it, under continuous testing time. It was used to interpret the heat flow phenomena and to calibrate a numerical model for further parametric analyses.

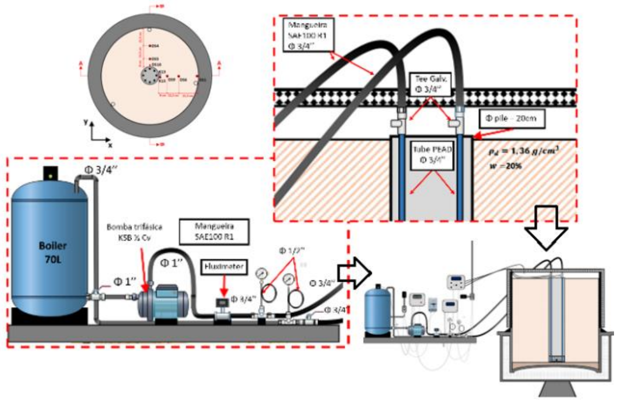

Figure 2. Setup of the calibration chamber, with 20 cm dia. GEP prototype and accessories for circulating heat flow.

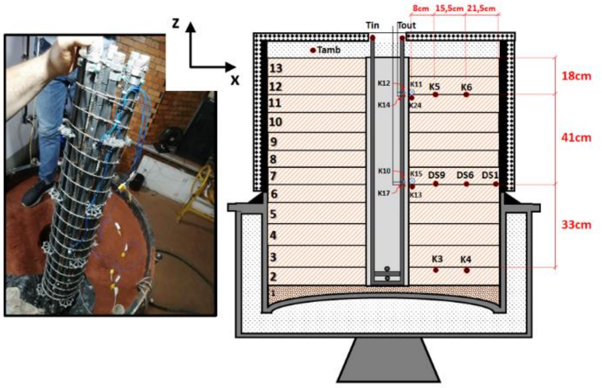

Figure 3. Photo and section details inside the chamber, with exchanger PEAD tubes (4U loop), compacted layers and thermal sensors.

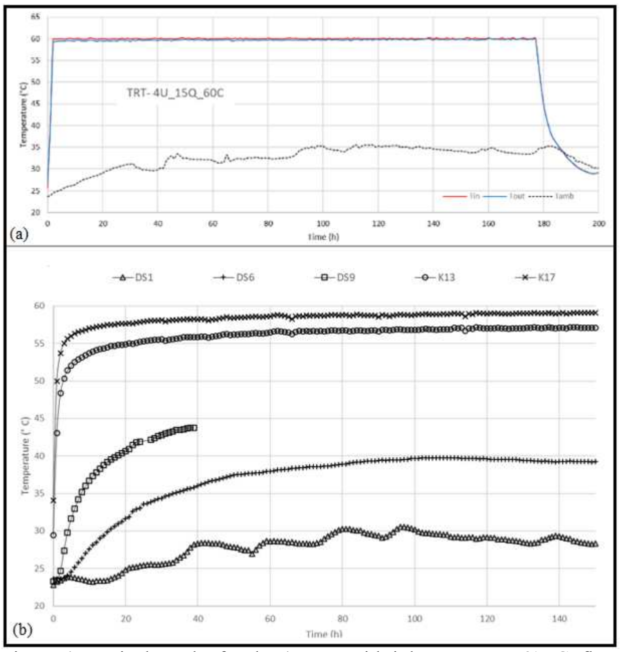

Figure 4. Typical results for the 4U test with inlet temp. T_{in} 61 °C, flow of 15 l/min and 200 hs of testing time, with (a) measured in/out and air temperatures and (b) sensor temperatures at layer 7.

2.2 *Thermal parameters of the soil*

The parameters of the compacted soil were defined by empirical methods that relate the thermal conductivity (k) and the specific heat capacity (Cp) with geotechnical variables of the layer as porosity, degree of saturation, mineralogy and granulometric distribution. This was done because thermal tests of the local soil deposit, or the compacted soil samples, have not been performed yet at this stage of the research.

The 1 m of compacted soil layer along the GEP prototype was divided into 12 distinct layers, in accordance with compaction procedures carried out during sample preparation. Lu et al. (2007) methodology was employed to derive the average thermal conductivity of each layer (k), taking in consideration the thermal conductivities of the minerals that form this soil, the porosity and the respective degree of saturation of the layers.

The k parameter for each layer is related to the (bulk) thermal conductivity of a laterized soil strata within the first 4 meters of the research site ($k_{mineral}$), since this is the zone where the soil sample was extracted. Although differences are expected, the superficial soil characteristics from the site, at this depth range, do not change considerably with depth (up to the 8/10 m transition zone before the typical regional saprolite of slate).

The mentioned (bulk) variable represents the bulk thermal conductivity of the minerals of this zone, as a whole, in accordance with their relative percentage within the soil mass. This percentage was defined with Xray diffractometric tests by Rodrigues (2017), i.e., exemplifying, this author has determined the following amounts of minerals for this soil: 34.9% of quartz, 34.6% of gibbsite, 22.1% of kaolinite, 6.6% of hematite, and few (< 1%) percentages of other minerals. A bulk value of 3.94 W/m.K was derived and used in Lu et al. (2007) method to estimate the avg. thermal conductivity k for each layer.

The specific heat capacity in J/kg.K was derived by the model of Johansen (1975), taking into consideration the dry unit and the specific apparent weight of the soil, the density of the water, the soil water content and the volumetric heat capacity of the water (as 4.18×10^6 J/m^3.K).

By adopting aforementioned steps, it was possible to derive Table 1 with the estimated thermal conductivities and specific heat capacities for each compacted layer (and density ρ).

Table 1. Thermal properties derived for each compacted layer

Layer	*ρ* (kg/m^3)	*k* (W/m.K)	*Cp* (J/Kg.K)
13	1570.34	1.333	1263.67
12	1679.45	1.524	1273.56
11	1629.48	1.434	1263.44
10	1739.61	1.633	1273.80
9	1679.45	1.524	1270.51
8	1670.27	1.507	1269.33
7	1660.07	1.490	1272.86
6	1639.68	1.449	1249.66
5	1620.30	1.416	1252.52
4	1629.48	1.431	1251.57
3	1520.37	1.243	1243.68
2	1510.18	1.229	1248.95

3 NUMERICAL ANALYSES

Numerical analyses were carried out to evaluate the efficiency of the heat exchange in a parameterized way, so to assess the influence of the adopted thermal / geometric variables. Also to gain initial insight into the modelling intricacies. Both numerical calibration and parametric simulations adopted similar geometric characteristics of the lab. tests, since their objective was to extend the experimental results to other cases.

A numerical commercial program was employed, which details, and stepwise procedure, are summarized next.

3.1 *Numerical software*

A commercial software based on the finite element method, denominated COMSOL Multiphysics v.5.2, was employed into calibration and parametric simulations. It is ideal since it offers specific modules that allow the simulation of the heat transfer and the flow regime inside the heat exchanger pipes. Moreover, it is quite flexible in terms of boundaries, geometric conditions and input parameters. It has a friendly output, easy to follow.

For instance, the heat conduction between concrete pile and surrounding soil was calculated with the “heat transfer in solids” module. The convective heat between heated fluid and pile wall, or within the circulating system´s fluid, adopted the “non-isothermal pipe flow” module, so to fully complement the heat phenomena process.

The step-by-step analysis procedure was given by:

• Geometry modeling: in this step, the 3D dimensions of the soil domain, piles and pipes were specified. The assumed geometry and limits of the model were the same as those used in the experimental test. The soil domain was modeled in a cylindrical shape with a diameter of 1.10 m and height equal to 1.08 m, similar to what was adopted in the lab. (as in Figure 3). Figure 5 depicts the adopted final mesh of the problem;

• Material properties: in this step, the properties of water, concrete and soil were specified, as for instance the soil´s density (ρ), thermal conductivity (k) and specific heat capacity (Cp), as previously defined in the present paper;

• Non-isothermal pipe flow convection parameters: Pipe properties were inputted as shape, internal diameter, wall roughness and material k. Friction factor between inner surface and fluid was estimated with Colebrook-White equation (Colebrook, 1939), in accordance to COMSOL´s recommendations. Initial values of atm. pipe pressure, fluid inlet/outlet positions, and inlet temperatures were then defined;

• Heat transfer in solids conduction parameters: Initial soil and pile temperatures (T) were given, and eventual variations;

• Mesh configuration: type of element and density. All three types of elements were tested (tetrahedral, prismatic, and hexahedral) and the tetrahedral type was used given its accuracy versus running time. Density of elements has also increased from pipe/pile outwards. The final mesh (Figure 5) respectively adopted 331, 25617 and 23727 elements for pipes, pile and soil;

• Simulation time: Normally of 50 hs of system´s flow. Note that all lab. tests took 200 hs but the numerical simulations showed no significant variation beyond 50 hs of running time, being also recommended by CEN/TC 341 2011;

At the end of the simulations, COMSOL Multiphysics software allowed the generation of various types of results, either visual or tabulated. Since the objective is to calculate the efficiency of the propagated thermal energy to the medium (ΔT), and the total heat flow per meter of pile (Q_L), the inflow and outflow temperatures were carefully checked.

The following equation was used to obtain the total heat flow per pile length at each numerical run (after 50 hs):

$$Q_L = C_w . \rho_w . q_{in} \left(\frac{T_{in} - T_{out}}{L_p} \right) \quad (1)$$

where

C_W – Specific heat capacity of water (4182 J/kgK)
ρ_W – water density (1000 kg/m^3)
q_{in} – water flow rate (m^3/s)
T_{in} – Inlet temperature (K); T_{out} – Outlet temperature (K)
L_p – Pile length (1 m)

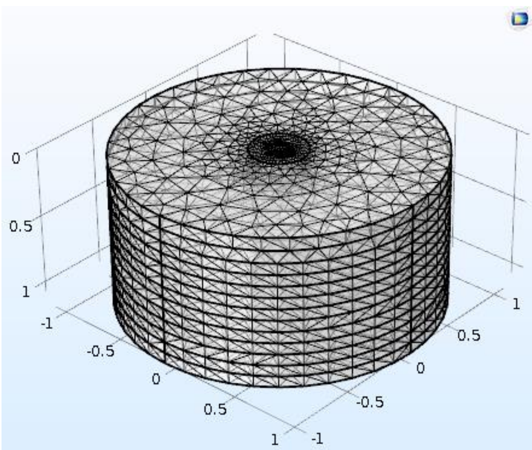

Figure 5. Mesh configuration adopted for numerical analyses.

3.2 *Model calibration*

Calibration was carried out by inputting previous parameters into the software discretized mesh and running the problem for a 50 hs total time. The initial soil T of 23.5°C and water inflow T_{in} of 61°C at 15 l/min was also adopted. The calibration was evaluated by comparing the experimental versus simulated thermal energy efficiency ΔT, or inlet/outlet temp. differences, as shown in Figure 6.

As it can be clearly noted, the differences between the results were reasonably low, so to suggest that the numerical modelling was able to simulate the thermal phenomena quite well, besides of some minor limitations.

Some of them relate to boundary conditions of the calibration chamber. Indeed, the boundary was not fully exempt of the thermal influence from the pile, and from external temperature changes, and DS1 temperature sensor (Figure 4) was clearly tampered. Unfortunately, the chamber was limited in size, and insulation problems were noticed after such tests. Boundary effects are therefore present in both compared results, which does not invalidate the comparison for most of the chamber inner section but must be properly dealt with in future experimental procedures. This aspect will be commented later.

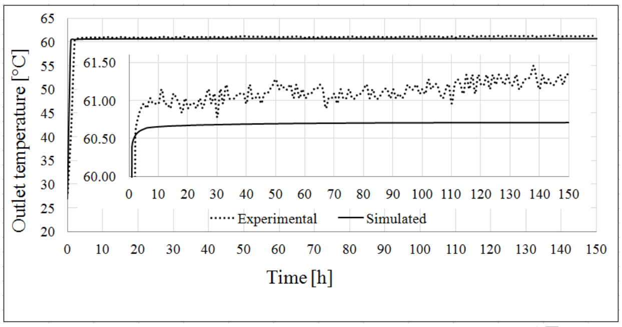

Figure 6. Calibration via lab. vs. experimental comparison of ΔT

3.3 *Parametric analyses*

The parametric analyses tried to cover distinct situations that have not been performed in the laboratory, given time constraints and proper equipment control. It will surely serve for future decisions in terms of large-scale simulations, so to assess the field performance of real design works.

Based on the calibrated model and on possible arrangements for the thermally active pile, the following arrays and terminology were adopted:

• Pipe layout: XU, where X indicates the number of pipe loops inside the pile, and U means the loop format;

• Fluid flow: Q + X, where Q is the flow reference and X indicates the water flow rate in liters per minute. It is either 15 or 30 l/min;

• Fluid inlet temperature: T + X, where T is the temp. reference and X indicates the temperature value in degrees celsius. It is either 20, or 40 or 61 °C.

Table 2 presents all combinations used to parametrize the problem, and to gather knowledge on heat thermal efficiency at distinct (laboratory) simulated scenarios. Notice that the experimental results used to calibrate the model, which data is depicted in Figures 4 and 6, are given in this table by the terminology 4U-Q15-T61.

It shall be noticed that the use of 61 degrees, rather than 60 in both experimental and numerical analyses is adopted due a mistake during the laboratorial setup. There was a resolution problem with the temperature sensor during some of the tests, that allowed an error of plus 1°C in the input value. This problem was unfortunately noticed only after finalizing some of the tests, and forced all of them to continue with a input temperature T_{in} of 61°C.

Table 2. Parametric combinations for numerical analyses

Pipe Layout	Flow (l/min)	Inlet Fluid Temperature (T_{in})		
		20°C	*40°C*	*61°C*
U	Q15	U-Q15-T20	U-Q15-T40	U-Q15-T61
	Q30	U-Q30-T20	U-Q30-T40	U-Q30-T61
2U	Q15	2U-Q15-T20	2U-Q15-T40	2U-Q15-T61
	Q30	2U-Q30-T20	2U-Q30-T40	2U-Q30-T61
3U	Q15	3U-Q15-T20	3U-Q15-T40	3U-Q15-T61
	Q30	3U-Q30-T20	3U-Q30-T40	3U-Q30-T61
4U	Q15	4U-Q15-T20	4U-Q15-T40	4U-Q15-T61
	Q30	4U-Q30-T20	4U-Q30-T40	4U-Q30-T61

4 RESULTS AND DISCUSSION

To evaluate the thermal influence of the TRT test in the surrounding medium, temperature values were numerically derived in distinct positions both within the pile (depths of 18 cm, 59 cm and 92 cm), and in the soil (at radial distances from the pile axis of 10 cm, 18 cm, 33.5 cm and 55 cm) for some of the layouts depicted in Table 2.

For instance, Figure 7 presents the numerically simulated temperatures of the test model 4U-Q15-T61 along depth, from 0 to 150 hs of thermal operation. This figure demonstrates that temperature differences (heat carrier fluid to inner pile value) tend to be maximized at early stages of operation, as operation time proceeds, decreasing afterwards. Hence, efficiency of the heat exchange process does reduce with time, a feature already noticed in other (lab. or numerical) experiments. Moreover, the pipe temperature increases more substantially along time at mid-height section, as the heat flux is unidirectional towards the chamber horizontal borders, whereas it is bidirectional at top and bottom positions given the existing upper and lower frontiers. In other words, fluid/pile temperature differences (and efficiency) are higher at the extremities, rather than at the pile´s mid-height position.

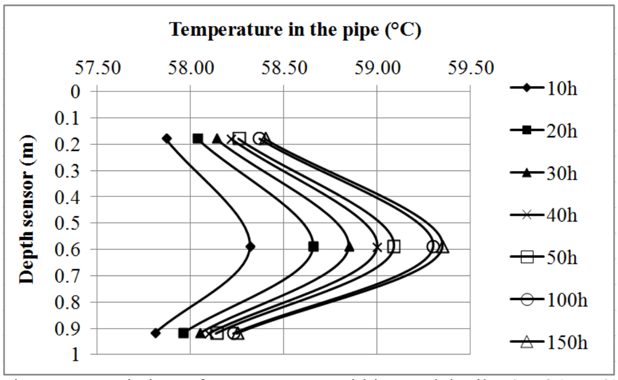

Figure 7. Variation of temperatures within model pile 4U-Q15-T61 during thermal loading operation (up to 150 hs).

Figure 8 illustrates this same test model in terms of a longitudinal cross section of the pile and chamber at the final 150 hs of thermal operation. Isothermal lines at distinct points along the chamber are depicted in accordance with their values in Celsius, as presented in the corresponding legend. One can notice that the zone of thermal influence has extended up to the inner wall of the calibration chamber, implying that some sort of boundary effect might influence the experimental results, given the limited radius of the employed chamber. Unfortunately, this experimental bias is of difficult solution, as larger diameter chambers could not be available for the present experiment.

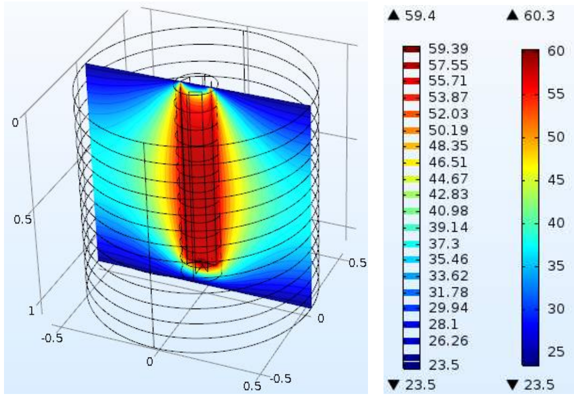

Figure 8. Temperature contours (Celsius) for a longitudinal cross section of model pile 4U-Q15-T61 at 150 hs of thermal loading.

This latter figure is complemented by Figure 9, where temperature contours for the same 4U-Q15-T61 model are compared to lab. data at a mid-height section of the chamber (59 cm), where the temperature DS sensors were located (see Figure 3).

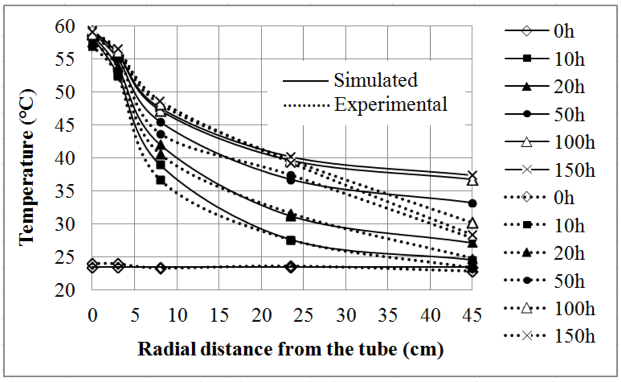

Figure 9. Experimental and numerical line contours for a mid-height cross section of model pile 4U-Q15-T61 at distinct time intervals.

As it can be noticed in this latter figure, experimental and numerical comparisons are good up to few centimeters to the chamber border (around 10 cm or so). At DS1 sensor the experimental T was 28.3ºC after 150 hs of thermal operation, which has contrasted well with the 37.4ºC prevision. Given the reasonably good match in inner chamber positions, this discrepancy is estimated to be due to both previously commented effects, i.e., the limited size of the chamber (increasing numerical Ts), and an improper insulation at the border (decreasing experimental Ts).

In order to gather an approximate overview of the distinct efficiencies of the numerical models, which are intrinsically related to the input parameters/characteristics of each of them (see Table 2), thermal gradients were determined at each specific modelled condition. This is shown in Figure 10. Notice that such gradients relate the difference between input and output temperatures of the heat carrier fluid, i.e. the thermal gradient ΔT (T_{in}-T_{out}).

Based on this figure some main observations can be drawn:

- Differently to what is commonly found in literature, better efficiencies or heat exchange between pile and surrounding soil (expressed in terms of ΔT) were noticed with lower velocity flows rather than higher ones. This is valid at all situations of assigned fluid T_{in}, and seems to be related to the fact that at lower velocities the fluid in turbulent state has more time to exchange heat with the pile, thus increasing the thermal exchange;

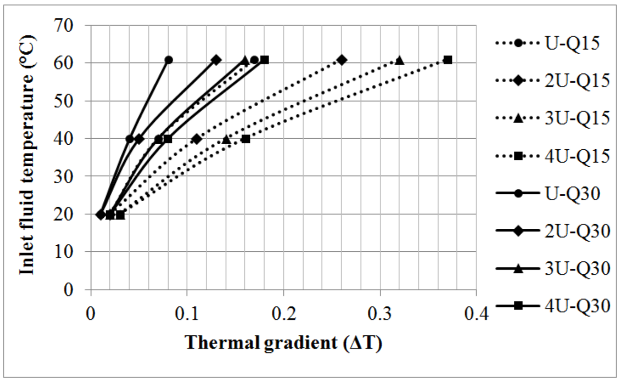

Figure 10. Inferred numerical gradients of temperature for all simulated test models.

- Similarly to what is commonly found in literature, thermal exchange is strongly dependent on pipe configuration, and higher exchange or efficiency is found for more densely packed configurations, i.e., increases from U to 4U at any velocity flow. Nevertheless, this will also speed thermal saturation within the chamber (an effect not studied at this stage), where soil temperatures approach and reach the (constant) inlet temperature of operation, ceasing exchange.

5 CONCLUSIONS

This paper has summarized the initial stages of an experimental testing program with a thermally active prototype pile immersed into an unsaturated compacted medium. The studied system tries to simulate distinct and extreme operational conditions in a common tropical soil of the Midwest region of Brazil, where investment for this new technology (in South America) may prove to be worthy to sustainably climatize both agribusiness and traditional type structures.

Initial experiments have revealed promising trends of thermal exchange within elements of the system. On the other hand, biased results at the chamber´s border, due to explained reasons, were also noticed. This setback was important to establish experimental corrections to the procedures. Numerical analyses carried out with such experiments have also revealed encouraging comparisons, indicating that model selection and parameter usage are both in the right direction.

The few results gathered so far indicate a strong dependence between the thermal gradient of the prototype pile with the velocity of the heat carrier fluid. The configuration of the heat exchanger pipes was also of relevance and must be taken on account on future setups.

The series of experiments, and their acquired experience, has undoubtedly helped in the configuration of future simulations. They also served to back up the numerical modelling, so to obtain further parametric predictions in closer harmony to more realistic, operational, (local) conditions. The research may eventually assist in developing sustainable design projects for the thermal climatization of structures founded on the typical tropical, unsaturated soil, of the central region of Brazil.

6 ACKNOWLEDGEMENTS

The first author is grateful to the Braz. Council for Research and Development (CNPq) for the fellowship no 204571/2018-9 that allowed his postdoc at the Univ. of Lisbon in Portugal, in 2019. Acknowledgement for research grants and scholarships from both sponsorship Brazilian institutions CNPq and CAPES to the co-authors is also given herein.

7 REFERENCES

Abdelaziz, S. and Ozudogru, T. Y. 2016. Non-uniform thermal strains and stresses in energy piles. *Environmental Geotechnics*, 3(4), 237–252.

Ahmadipur, A. and Basu, P. 2016. Temperature-induced alterations of the shaft and base resistances of a model geothermal pile in dry sand. *Proc. Geo-Chicago 2016 Sustain. Resiliency Geotech. Eng*. GSP 269, Chicago, 155–165.

Akrouch, G. A., Sánchez, M. and Briaud, J. L. 2014. Thermo-mechanical behavior of energy piles in high plasticity clays. *Acta Geotechnica*, 9(3), 399–412.

Akrouch, G. A., Sánchez, M. and Briaud, J. L. 2015. Effect of the unsaturated soil condition on the thermal efficiency of energy piles. *Geotechnical Special Publication*, GSP 256, 1618–1627.

Akrouch, G. A., Sánchez, M. and Briaud, J. L. 2016. An experimental, analytical and numerical study on the thermal efficiency of energy piles in unsat. soils. *Computers and Geotechnics*, 71, 207–220.

Bandeira Neto, L. A. 2015. Experimental study of the thermal response geothermal energy piles foundations in unsaturated soil. São Carlos Eng. School of São Paulo State Univ., *MSc Thesis*, 130 p.

Bourne-Webb, P. J. and Bodas Freitas, T. M. 2020. Thermally-activated piles and pile groups under monotonic and cyclic thermal loading–A review. *Renewable Energy*, 147, 2572–2581.

Brandl, H. 2006. Energy foundations and other thermo-active ground structures. *Geotechnique*, 56(2), 81–122.

Colebrook, C. F. 1939. Turbulence flow in pipes, with particular reference to the transition region between the smooth and rough pipe laws. *Journal of the Inst. of Civil Engineers*, 11, 133-156.

CEN/TC 341. 2011. Geotechnical investigation and testing-Geothermal testing-Determination of thermal conductivity of soil and rock using a borehole heat exchanger. *Eurocode Standard N525*.

Di Donna, A., Rotta Loria, A. F. and Laloui, L. 2016. Numerical study of the response of a group of energy piles under different combinations of thermo-mechanical loads. *Computers and Geotechnics*, 72, 126–142.

Goode, J. C. and McCartney, J. S. 2015. Centrifuge modeling of end-restraint effects in energy foundations. *Journal of Geotechnical and Geoenvironmental Engineering*, 141(8), 1–13.

Johansen, O. 1975. Thermal conductivity of soils. *Ph.D. Thesis,* CRREL Draft Translation 637, Trondheim.

Lu, S., Ren, T., Gong, Y. and Horton, R. 2007. An improved model for predicting soil thermal conductivity from water content at room temperature. *Soil Science Society of America Journal*, 71(1), 8-14.

Murphy, Kyle D., McCartney, J. S. and Henry, K. S. 2015. Evaluation of thermo-mechanical and thermal behavior of full-scale energy foundations. *Acta Geotechnica*, 10(2), 179–195.

Olgun, C. Guney, Geyin, M. and Ozudogru, T. Y. 2017. Long-term performance of heat exchanger boreholes at different climatic conditions. *Geotechnical Special Publication*, GSP 280, 153–164.

Orozco, H.C. 2016. Validation of the TRT for the parametric study of the heat exchange of a geothermal pille in a tropical soil. University of Brasília, *MSc Thesis*, 150 p. (In Portuguese).

Rodrigues, S. M. 2017. Mineralogical and microstructural characterization of a weathered profile in Brasilia. State University of Goiás, *B.Sc. Final Project*, 133 p. (In Portuguese).

Rotta Loria, A. F., Vadrot, A. and Laloui, L. 2018. Analysis of the vertical displacement of energy pile groups. *Geomechanics for Energy and the Environment,* 16, 1–14.

Salciarini, D., Ronchi, F. and Tamagnini, C. 2017. Thermo-hydro-mechanical response of a large piled raft equipped with energy piles: a parametric study. *Acta Geotechnica*, 12(4), 703–728.

Sani, A.K., Singh, R. M., Cavarretta, I. and Bhattacharya, S. 2018. Heat storage performance of a pile heat exchanger installed in partially saturated swelling clay. *Proc. 7th Int. Conf. Unsaturated Soils*, Hong Kong, pp. 1–6.

Sani, A.K., Martand, R., Amis, T. and Cavarretta, I. 2019. A review on the performance of geothermal energy pile foundation , its design process and applications. *Renewable and Sustainable Energy Reviews,* 106(February), 54–78.

Sani, A.K. and Singh, R. M. 2020. Response of unsaturated soils to heating of geothermal energy pile. *Renewable Energy*, 147, 2618–2632.

Sousa Júnior, R.P. 2017. Parametric study of the thermal response of geothermal pile groups in a tropical soil typical from the Federal District. University of Brasília, *MSc Thesis*, 145 p. (In Portuguese).