Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
© 2022 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-4-1

First Thermal Response Test (TRT) for energy geo-structure applications in Mexico

Premier Test de Réponse Thermique (TRT) pour les applications de géostructure thermiques au Mexique

Norma Patricia López-Acosta, Abigail Marisol Rivera-Martínez & David Francisco Barba-Galdámez
Instituto de Ingeniería, UNAM, México, nlopeza@iingen.unam.mx

ABSTRACT: Energy geo-structures are a viable alternative to reduce the environmental impact of the growing energy demand for space conditioning in Mexico. The effective design of these systems requires an accurate estimation of certain thermal properties, such as ground thermal conductivity, its undisturbed temperature, and the Ground Heat Exchanger (GHE) thermal resistance. These parameters are usually measured *in situ* by a Thermal Response Test (TRT). A standard TRT consists of injecting heat into the ground via water circulation in a closed loop of a GHE. Although TRTs have been in use for years in different countries, to the authors' knowledge they have not yet been implanted in Mexico. This paper presents the results of a TRT carried out in the first energy pile constructed in Mexico. The test was performed with a mobile TRT apparatus constructed by the II-UNAM and represents an invaluable resource for the future development of energy geo-structures in Mexico.

RÉSUMÉ: Les géostructures énergétiques sont une alternative viable pour réduire l'impact environnemental de la demande croissante d'énergie pour la climatisation spatiale au Mexique. La conception efficace de ces systèmes nécessite une estimation précise des certaines propriétés thermiques, telles que la conductivité thermique du sol, sa température non perturbée et la résistance thermique de l'échangeur de chaleur (GHE). Ces paramètres sont généralement mesurés *in situ* par un test de réponse thermique (TRT). Un TRT standard consiste à injecter de la chaleur dans le sol via la circulation de l'eau en boucle fermée d'un GHE. Bien que les TRT soient utilisés depuis des années dans différents pays, à la connaissance des auteurs, ils n'ont pas encore été implantés au Mexique. Cet article présente les résultats d'un TRT réalisé dans la première pile d'énergie construite au Mexique. Le test a été réalisé avec un appareil mobile TRT construit par l'II-UNAM et représente une ressource inestimable pour le développement futur des géostructures énergétiques au Mexique.

KEYWORDS: Energy piles; thermal response test; ground-source heat pumps; thermal conductivity.

1 INTRODUCTION

The need to reduce carbon emissions to tackle climate change has increased the demand for clean energy. In Mexico, the federal government has committed to lower the country's greenhouse emissions by 22% by 2030 (Altamirano *et al.* 2016). This target is ambitious, considering that the country is highly dependent on fossil fuels, which accounts for 83% of the energy supply (SENER 2019). Moreover, climate change and the development of northern and southeastern states (where extreme and humid subtropical climates predominate, respectively) have produced an increase in energy consumption for space conditioning, which is mostly fulfilled with traditional HVAC systems (Oropeza-Perez and Petzold-Rodriguez 2018). Recently, ground-source heat pump systems (GSHPs) and energy geo-structures have been proposed as a viable alternative to reduce the carbon footprint of this growing demand (Gutiérrez-García and Martínez-Estrella 2012, López-Acosta *et al.* 2019). In particular, energy piles are foreseen as an attractive option since traditional piles are a common foundation element for commercial, industrial, and residential buildings in Mexico's largest cities. In these systems, building's deep foundations are equipped with pipe loops and work as ground heat exchangers (GHEs) (Brandl 2006).

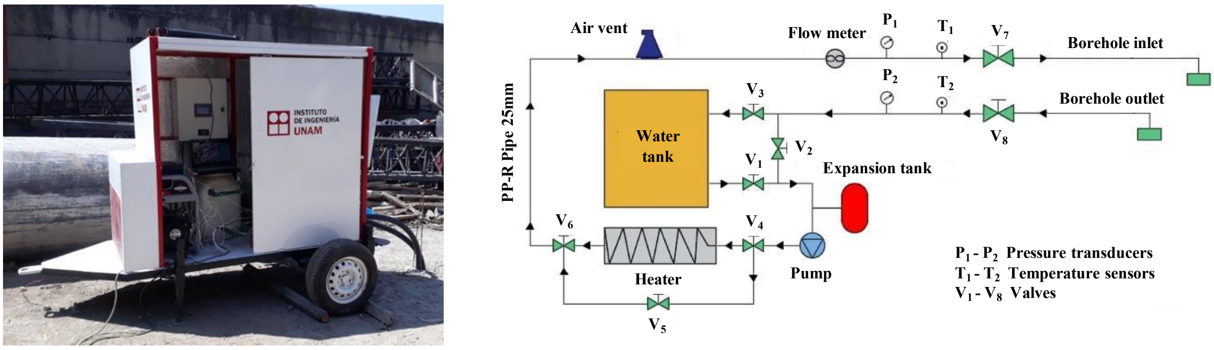
An efficient design of GSHP and energy geo-structure systems requires an accurate characterization of the steady state thermal resistance of the GHE (R_b), the thermal conductivity of the surrounding ground (λ_g) and its undisturbed temperature (T_0) (Loveridge *et al.* 2017). Currently, the Thermal Response Test (TRT) is the most widely used method for the determination of these parameters (Low *et al.* 2015). The TRT is a large-scale transient field test that involves circulating a fluid though pipes embedded in the ground for a period of 48 to 72 h, while measuring the inlet and outlet of the loop. The data is then fitted to a heat transfer model. Traditionally, TRTs have been restricted boreholes and piles of small diameter, i.e., no more than 300 mm (GSHP 2012). The above is due to concerns about the practical and economic implications associated with the duration test required to apply conventional steady-state analytical models (Laloui and Rotta Loria 2020). However, recent studies have shown that accurate results can be obtained from TRT in larger piles if adequate interpretation methods are selected, such as transient models and two- or three- dimensional numerical models (Loveridge *et al.* 2014, Jensen-Page *et al*. 2019).

Although TRTs have been in use for years, to the authors' knowledge they have not yet been implanted in Mexico. Moreover, despite its growing importance, the information about the thermal properties of national soils is scarce (Silva-Aguilar *et al*. 2018, Portillo-Arreguín *et al*. 2019). This paper presents the results of the first TRT carried out in an energy pile in the country. The tested element is part of the foundation system of a cutting-edge project named "Residence C73" which is the first building with energy piles in Mexico. The test represents a starting point for the future development of energy geo-structures in the country.

2 EXPERIMENTAL SETUP

2.1 *TRT Apparatus*

The experimental apparatus was designed and constructed by Institute of Engineering at UNAM (II-UNAM) according to the International Energy Agency (IEA) recommendations (IEA-ECES, 2013). It is a mobile device contained in a small single axle trailer (Fig. 1a). The equipment consists of a 0.5 hp circulation pump, one water heater element in the range of 3.7 kW, a water supply/purge tank, an expansion tank, polypropylene random copolymer (PP-R) pipes and valves. The measuring devices include a flow meter, two platinum resistance thermometers (PT-100) with an accuracy of ± 0.15 °C, and two



(a) (b)

Figure 1. (a) The first mobile Thermal Response Test (TRT-II-UNAM) apparatus in Mexico and (b) schematic apparatus layout.

pressure transducers (Fig. 1b). Additionally, a DHT-22 sensor was incorporated to monitor ambient temperature during the test. The instrumentation is connected to a control panel that manages the heating mode and waterflow. The inlet and outlet fluid temperature, atmospheric temperature, flow rate and water pressure are transmitted and recorded into this panel. All the instrumentation and control panel are contained within the trailer.

2.2 *Site stratigraphy and project description*

The experimental site is located in the northwestern hills of Mexico City, Mexico. The mean annual temperature in the area is 17.8 °C, with mean monthly extremes of 27.4 °C in April and 5.1°C in January. The soil stratigraphy at the site was obtained from geotechnical investigations based on standard penetration tests (SPT) and consists of six strata. The top stratum is formed by backfill material extending up to 0.6 m deep. Beneath the fill, there is a 6-m layer of andesitic silty sand locally known as Blue Sands. It overlies a thin layer of poorly graded gravels with an average thickness of 1.5 m, followed by a 3.5-m stratum of silty gravel with sand. The fifth layer extends up to a depth of 16 m and consists of a grayish brown poorly graded sand. The last stratum is formed by andesitic rock fragments with a Rock-Quality Designation (RQD) of 6%. No groundwater was encountered during the site investigation, so it is assumed to be below the sounding depth (18 m).

The "Residence C73" project is a one-story building provided with state-of-the-art facilities. The building is supported on eight bored piles of two different diameters: 100 cm (D-1) and 80 cm (D-2). Six of these were designed to work as energy piles (Fig. 2). The TRT was conducted on a 15.5-m long reinforced concrete pile with a diameter of 0.8 m. It was equipped with four U-loop pipes connected in series with a separation of 35 cm. The pipes were made of high-density polyethylene (HDPE) with an outer diameter of 3.34 mm and an inner diameter of 2.54 cm (Fig. 3).

The heat exchanger pipes were attached to the inside of the reinforcing cages with zip-ties at a distance of at least 75 mm from each vertical reinforcement (Fig. 4a). Ninety-degree elbow fittings were used to form the U-loops. The pipes were joined by butt fusion following the pipe manufacturer's procedures, filled with water and a pressure test was conducted to verify their leak tightness (Fig. 4b). The reinforcing cages were lifted and lower into an uncased hole with a crane (Fig. 4c). Finally, high-slump concrete was poured with a tremie to avoid excessive segregation and minimize any potential damage of the loops (Fig. 4d).

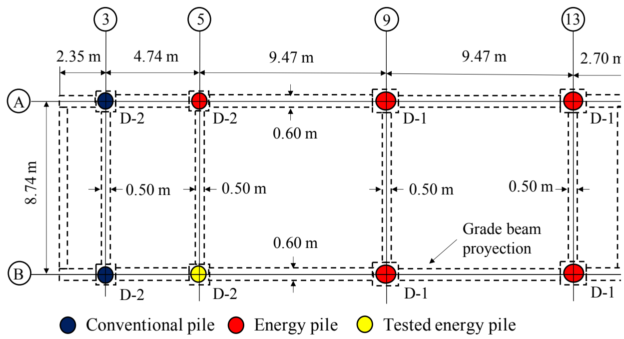
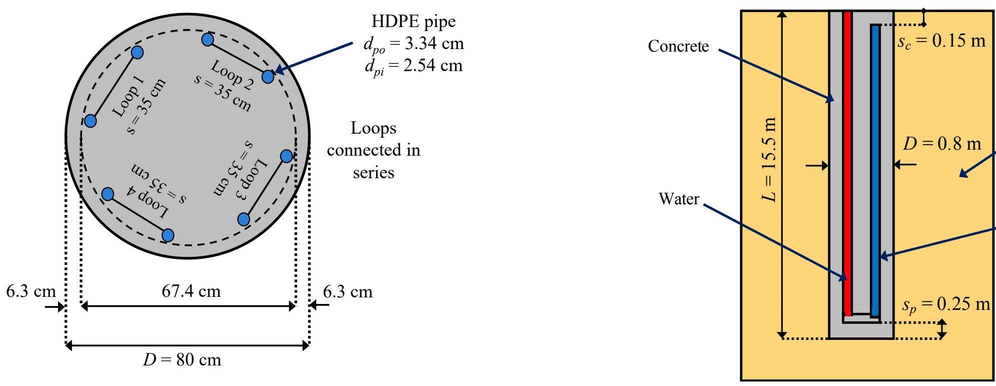


Figure 2. Foundation layout of "Residence C73" Project. D-1: 100-cm diameter pile, D-2: 80-cm diameter pile.

2.3 *TRT procedure*

The TRT was carried out two months after the concrete pouring. Before starting the test, the undisturbed ground temperature was measured by lowering a temperature sensor (PT-100) into one leg of the U-loop, as suggested by Gehlin and Nordell (2003). Temperature was recorded at every 1 m depth.



(a) (b)

Figure 3. (a) Detail of pile cross section, and (b) pile geometry. Note: D = pile diameter, d_{po} = outer pipe diameter, d_{pi} = inner pipe diameter, HDPE: high-density polyethylene, L =pile length, s = loop separation, s_c = separation between loop and pile head, s_p = separation between loop and pile base.

(a) (b) (c) (d)

Figure 4. Construction photos: (a) reinforcement cages with heat exchangers, (b) pressure test, (c) lowering of reinforcement cage into the uncase hole, and (d) concrete pouring.

To stabilize the fluid temperature and check for any possible leakage before heating, water was circulated through the loops during 30 minutes with the heater turned off. Then, a 60-hour heat injection test was performed using a nominal heating power of 1.7 kW (110 W/m). All measured data (inlet and outlet temperature, water pressure, flow rate and ambient temperature) were simultaneously recorded at 10-second intervals. Both the flow rate and the power input from the heater remained nearly constant during the test, with average values of 0.557 m^3/h and 1.704 kW, respectively (Fig. 5).

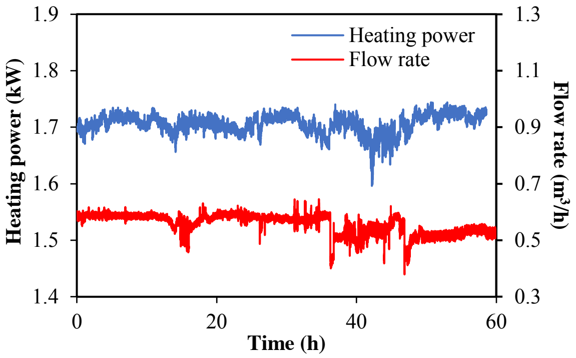


Figure 5. Heat power and flow rate during the TRT performed.

3 ANALYSIS METHOD

The TRT data were interpreted using the transient procedure proposed by Loveridge *et al*. (2013). This method uses empirical G-functions specifically developed for the ground (G_g) and the pile (G_c), which described the transient response of the ground surrounding the piles and the concrete, respectively. Thus, the temperature change of the circulating fluid during heating (ΔT_f) can be calculated by summing the temperature change across the pipes and the G-functions as:

$$\Delta T_f = qR_p + qR_cG_c + \frac{q}{2\pi\lambda_g}G_g \quad (1)$$

where q is the heat transfer rate per meter length of the energy pile, R_p is the resistance of the pipes (including the fluid) and R_c is the resistance of the concrete part of the pile. R_p can be calculated as the sum of the pipe conductive resistance ($R_{p,cond}$) and the pipe convective resistance ($R_{p,conv}$) as follows:

$$R_p = R_{p,cond} + R_{p,conv} \quad (2)$$

where:

$$R_{p,cond} = \frac{\ln(r_o/r_i)}{2n\pi\lambda_p} \quad (3)$$

and:

$$R_{p,conv} = \frac{1}{2n\pi r_i h_i} \quad (4)$$

where r_i is the pipe inner radius, r_o the pipe outer radius, λ_p the pipe thermal conductivity, n the number of pipes within the pile, and h_i the heat transfer coefficient that is determined using the Gnielinksi correlation (Gnielinski, 1976).

Given the form of the G-functions, it is possible to determine λ_g and R_c from the time series data collected during the test using a non-linear least-squared inversion technique. The above was done in this research using the curve fitting toolbox of MATLAB®, based on the Levenberg-Marquardt algorithm (Marquardt, 1963).

Both G_g and G_c functions take the following form:

$$G = a[\ln F_0]^7 + b[\ln F_0]^6 + c[\ln F_0]^5 + d[\ln F_0]^4 + e[\ln F_0]^3 + f[\ln F_0]^2 + g[\ln F_0] + h \quad (5)$$

where the constants a to h depend on the pipe positions and the aspect ratio of the pile ($AR=2L/D$) (Table 1), and F_0 is the Fourier number calculated as:

$$F_0 = \frac{\alpha_g t}{r_b^2} \quad (6)$$

where α_g is the soil thermal diffusivity, t is the elapsed time since application of the heat flux and r_b is the pile radius.

Table 1. Values of constant used with the pile and concrete G-functions (Loveridge *et al*., 2013).

Constant	*Concrete G-function* (G_c)[1]	*Pile G-function* (G_g)[2]
a	0	2.68×10^{-7}
b	-1.438×10^{-5}	-1.30×10^{-5}
c	1.276×10^{-5}	1.827×10^{-4}
d	9.534×10^{-4}	-9.15×10^{-5}
e	1.307×10^{-4}	-0.01434
f	-0.02446	0.05634
g	0.07569	0.3722
h	0.921	0.3989

[1] G_c=0 for F_0<0.01, and G_c=1 for F_0>10
[2] G_g=0, for F_0<0.25

According to Loveridge *et al*. (2014), the steady state thermal resistance of the GHE (R_b) can then be calculated as:

$$R_b = R_p + R_c \quad (7)$$

4 RESULTS AND DISCUSSION

The TRT test was performed from December 5th to 8th 2020, with ambient temperatures ranging from 13 °C to 25 °C (Rivera-Martínez 2021). The initial temperature profile recorded by the PT-100 (Fig. 6) shows that the ground temperature at the site is relatively constant, ranging from 17.8 °C to 19.7 °C, with an average value of 18.8 °C. These values provide adequate conditions for both cooling and heating demands of the project.

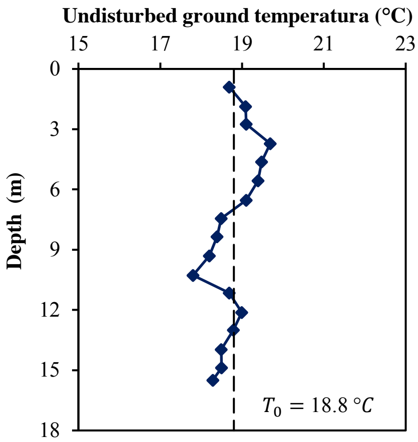


Figure 6. Temperature profile along the pile. Note: T_0 = undisturbed temperature of the ground.

An estimated value of 0.012 m·°C·W^{-1} was obtained for pipe resistance (R_p) considering the pipes geometries, their thermal properties and the average flow rate, according with Eqs. (2) – (4). To determine the values of the thermal conductivity of the surrounding ground (λ_g) and the resistance of the concrete part of the pile (R_c), the Loveridge *et al.* (2013) transient model was fitted to the average fluid temperature variation measured during the TRT, as described in section 3. The analysis indicated that λ_g = 1.63 W·m^{-1}·°C^{-1} and R_c = 0.078 m·°C·W^{-1}. Thus, the steady state thermal resistance of the GHE (R_b) is approximately 0.09 m·°C·W^{-1}. These values are similar to those reported in the literature for energy piles (Loveridge, 2012) and unsaturated gravels and sands (Dalla Santa *et al.*, 2020).

The transient model showed a good agreement with the field experimental data. It is capable to capture the general trend of the temperature variation and replicate the measured data with high accuracy, even for early times (Fig. 7). Goodness-of-fit between the predicted and measured values was assessed using the root mean square error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(T_{est,i} - T_{mea,,i}\right)^2}{N}} \quad (8)$$

where $T_{est,i}$ is the estimated fluid temperature variation, $T_{mea,i}$ is the measured value and N is the number of data. *RMSE* is an estimator of the standard deviation of the residuals (difference between the predicted values and the measured data) –the smaller the *RMSE* value, the better the estimation–. For the study case, the RMSE is 0.2254, which confirms the capacity of the model to replicate the *in situ* behavior of the TRT.

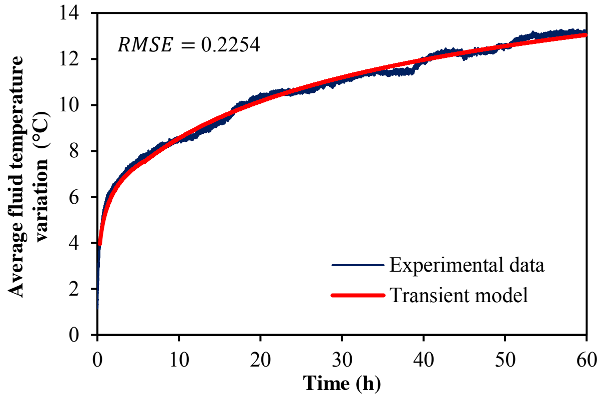


Figure 7. Visual fit of the transient model to the experimental data. Note: RMSE = root mean square error.

5 CONCLUSIONS

Energy geostructures are one of the most innovative techniques in the field of renewable energy to reduce greenhouse gas emissions caused by space conditioning systems. In particular, energy piles are foreseen as a viable alternative to traditional HVAC systems in Mexico. Currently, the first building that incorporates this technology in the country is under construction in Mexico City. The building, named "Residence C73" project, is founded on eight bored piles, six of which are equipped with heat exchanger pipe loops (energy piles). The efficient design of these structures depends on an accurate measurement of the thermal properties of the ground and the ground heat exchanger (GHE).

This paper presented the analysis of a Thermal Response Test (TRT) performed in one of the energy piles of the "Residence C73" project. The test was the first of its type developed in the country and was performed using a novel mobile TRT apparatus designed and constructed by the II-UNAM. Due to the characteristics of the experimental setup, a transient analytical model was employed to assess the TRT data. The experimental results indicated that the thermal conductivity of the ground is 1.63 W·m^{-1}·°C^{-1} and the steady state thermal resistance of the GHE is 0.09 m·°C·W^{-1}. These data are similar to those reported in the literature and have been used to enhance the preliminary design of the "Residence C73" energy piles.

The test described in this paper is part of a long-term research program to characterize the thermal properties of Mexican soils and represents a starting point for the future development of energy geo-structures in the country.

6 ACKNOWLEDGEMENTS

The authors acknowledge the companies PILOTEC and LBR&A for the logistic support to carry out the in-situ thermal tests at the "Residence C73" project.

7 REFERENCES

Altamirano J., Ortiz Sánchez E., Rissman J., Ross K., Fransen T., Brown Solá C., and Martinez J. 2016. Achieving Mexico's Climate Goals: An Eight-Point Action Plan. *Working Paper*. Washington, DC: World Resources Institute.

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

Dalla Santa G., Galgaro A., Sassi R., Cultrera M., Scotton P., Mueller J., Bertermann D., Mendrinos D., Pasquali R., Perego R., Pera S., Di Sipio E., Cassiani G., De Carli M., and Bernardi A. 2020. An updated ground thermal properties database for GSHP applications. *Geothermics* 85, 101758

Gehlin S. and Nordell B. 2003. Determining Undisturbed Ground Temperature for Thermal Response Test. *ASHRAE Transactions: Research* 109, 151–156.
Gnielinski V. 1976. New equation for heat and mass transfer in turbulent pipe and channel flow. *Int Chem Eng* 16, 359–368.
GSHPA (Ground Source Heat Pump Association). 2012. *Thermal pile design, installation and materials standards*. Milton Keynes, UK.
Gutiérrez-García A. and Martínez-Estrella, I. 2012. Estado actual de Desarrollo de las Bombas de Calor Geotérmico. *Geotermia*, 25 (2), 58-68 (in Spanish).
IEA ECES 2013. *Annex 21: Thermal response test (TRT). Final report*.
Jensen-Page L., Loveridge F., and Narsilio G.A. 2019. Thermal response testing of large diameter energy piles. *Energies* 12(14), 1–25.
Laloui L. and Rotta Loria A.F. 2020. Chapter 14 - Determination of design parameters for energy geostructures. In: Laloui L. and Rotta Loria A. F. (Eds.) *Analysis and Design of Energy Geostructures*. Academic Press, 821–932.
López-Acosta N.P., Barba-Galdámez D.F., and Sánchez M. 2019. Numerical Analysis of the Thermo-Mechanical Behavior of an Energy Pile in Mexico. In: Ferrari A. and Laloui L. (Eds.) *Energy Geotechnics. SEG 2018*. Springer Series in Geomechanics and Geoengineering. Springer, Cham, 147–154.
Loveridge F. 2012. *The thermal performance of foundation piles used as heat exchangers in ground energy systems*. PhD thesis, Faculty of Engineering and the Environment, University of Southampton, UK
Loveridge F. and Powrie W. 2013. Temperature response functions (G-functions) for single pile heat exchangers. *Energy* 57, 554–564.
Loveridge F., Low J., and Powrie W. 2017. Site investigation for energy geostructures. *Quarterly Journal of Engineering Geology and Hydrogeology* 50(2), 158–168.
Loveridge F., Powrie W. and Nicholson D. 2014. Comparison of two different models for pile thermal response test interpretation. *Acta Geotechnica* 9(3), 367–384.
Low J.E., Loveridge F.A., Powrie W., and Nicholson D. 2015. A comparison of laboratory and in situ methods to determine soil thermal conductivity for energy foundations and other ground heat exchanger applications. *Acta Geotechnica* 10(2), 209–218.
Marquardt D.W. 1963. An Algorithm for Least-Squares Estimation of Nonlinear Parameters. *Journal of the Society for Industrial and Applied Mathematics*,11(2), 431–441.
Oropeza-Perez I. and Petzold-Rodriguez A. 2018. Analysis of the Energy Use in the Mexican Residential Sector by Using Two Approaches Regarding the Behavior of the Occupants. *Applied Science* 8, 2136.
Portillo-Arreguín D.M., López-Acosta N.P., Barba-Galdámez D.F., Singh R.M. 2019. Thermal Properties of Mexico Basin Soils. In: López-Acosta N.P., Martínez-Hernández E., Espinosa-Santiago A.L., Mendoza-Promotor J.A., Ossa López A. (Eds.) *Geotechnical Engineering in the XXI Century: Lessons Learned and Future Challenges*. IOS Press, 2858–2863.
Rivera-Martínez A.M. 2021. Design and implementation of a thermal response equipment (TRT) for determining the thermal properties of soils. Master Thesis in Engineering. Universidad Nacional Autónoma de México, Mexico.
Secretearía de Energía – SENER. 2019. *Balance Nacional de Energía 2018*. Ciudad de México (in Spanish).
Silva-Aguilar O.F., Andaverde-Arredondo J.A., Escobedo-Trujillo B.A. and Benitez-Fundora A.J. 2018. Determining the In Situ Apparent Thermal Diffusivity of a Sandy Soil. *Revista Brasileira de Ciência Do Solo*, 42, 1–13.