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Probabilistic Analysis of Energy Piles Reliability Using Monte Carlo Simulations

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ABSTRACT: In this paper, the use of energy piles as an innovative geotechnical solution, which combines structural support with the sustainable benefits of geothermal energy, is evaluated through probabilistic analyses. Energy piles, functioning as both load-bearing foundations and heat exchangers, offer a significant opportunity to reduce carbon emissions while addressing heating and cooling demands in buildings. The study presented here employs a probabilistic approach based on Monte Carlo simulations to analyze the serviceability limit states of energy piles under varying thermal and mechanical loads. Key geotechnical parameters were characterized using the Menard Pressuremeter Test and incorporated into load-transfer models (t-z curves) to evaluate the thermo-mechanical responses of energy piles, particularly in terms of displacement, stress distribution, and structural integrity. Five temperature scenarios, ranging from -20°C to 0°C, were simulated to assess the performance variability of the proposed energy pile under extreme conditions. The findings reveal that temperature fluctuations have a significant influence on pile deformation and stress redistribution, underscoring the importance of integrating thermal considerations into design methodologies. The study highlights the potential for convenient adoption of energy piles in Mexico, especially in urban areas, to align with global sustainability goals. This work provides a framework for improving the efficiency and reliability of energy pile systems in Mexican geotechnical engineering. The adoption of energy piles in Mexico represents an opportunity to modernize geotechnical engineering while addressing critical energy and environmental challenges. This study promotes the application of more efficient and reliable systems, contributing to a sustainable urban development and a greener future.

KEYWORDS: Energy piles, geothermal energy, probabilistic analysis, serviceability limit state, Menard pressuremeter, sustainable construction.

1 INTRODUCTION

The demand for Heating, Ventilation, and Air Conditioning (HVAC) systems is rapidly growing in developing countries due to population growth, urbanization, and a warming climate (Dong *et al*., 2021). In Mexico, energy demand for cooling spaces is expected to double by 2100, particularly in the northern and southeastern states, as well as in coastal regions (Jiménez Torres *et al*., 2023). According to Khalfallah *et al*. (2016), air conditioning accounts for 30 - 70% of peak energy demand in hot climates, posing a significant challenge to the decarbonization of the building sector, which is heavily dependent on carbon-intensive sources (UNEP-IEA, 2020; Akhmetov *et al*., 2025). In Mexico, previous studies (IEA, 2018) suggest that cooling can account for more than a 25% increase in total CO_2 emissions by 2050.

Recently, energy geostructures have been proposed as a viable alternative to reduce the carbon footprint associated with the growing demand for space conditioning in Mexico (López-Acosta *et al*. 2019). This technique was pioneered in Europe during the 1980s (Laloui *et al*., 1999; Brandl, 2006; Adam and Markiewicz, 2009), but their adoption in Mexico remains limited despite favorable conditions. Figure 1 and 2 shows one of the first energy storage systems implemented west of Mexico City.

Figure 1. Placement of reinforcing steel inside the borehole (Hernandez, 2023)

Figure 2. Cast-in-place energy pile (Hernandez, 2023)

Energy geostructures are structural elements that function as heat exchangers of a Ground Source Heat Pump (GSHP) system. By using a sustainable energy source (shallow geothermal energy) and due to its high efficiency, they help to reduce CO_2 emissions, energy consumption, and maintenance costs of HVAC systems (Brandl, 2006). Energy piles are a particularly appealing choice since traditional piles are a common foundation element for buildings in Mexico.

Compared to conventional pile foundations, energy piles are subjected to long-term cyclic thermal loads during service, following the building's heat requirements. (Loveridge *et al*., 2020). Temperature changes cause the expansion or contraction of energy piles and the surrounding soil. In some cases, they can cause additional settlement, tensile or compressive stresses, or mobilize the shear strength of the soil at the pile shaft (Abuel-Naga *et al.,* 2015).

The magnitude and distribution of the additional axial stresses and strains along the pile depend on the type of soil surrounding it, the restraints at the pile head and base, the pile geometry, and its length (Sani *et al*., 2019).

In recent years, several analysis approaches have been developed, including synthetic design charts, load-transfer methods, and numerical modeling (Cunha and Bourne-Webb, 2022). Nevertheless, their geotechnical design presents several challenges due to uncertainties in soil parameters, applied loads (thermal and mechanical), and model errors, among others. In this context, traditional deterministic design methods, which rely on global safety factors, may be insufficient to quantify the real risk associated with the performance of energy piles. Recent studies (Xiao *et al.* 2016; Wang *et al.*, 2017; Luo and Hu, 2019; Song *et al.*, 2023; Barba-Galdámez *et al.*, 2024) have proposed reliability-based design approaches to evaluate the limit states of energy piles, which allow the explicit incorporation of the uncertainty of input parameters in the design process. The Monte Carlo simulation method emerges as a robust and flexible tool for assessing system reliability, as it can easily handle complex and non-linear limit state functions, such as those involved in the thermo-mechanical analysis of piles.

This study addresses uncertainties in energy design by applying a probabilistic framework to assess serviceability limit states under thermal-mechanical loading. The analysis leverages the Menard Pressuremeter Test (PMT 2012) to characterize soil parameters and Monte Carlo simulations to evaluate displacement.

2 THERMO-MECHANICAL ANALYSIS OF ENERGY PILES

The load transfer method is one of the most commonly used procedures to estimate the axial response of isolated piles, due to its speed, flexibility, and low computational requirements. This method involves dividing the pile into segments connected by non-linear springs. The transfer functions then represent either the mobilization of friction in the shaft or the stress at the base due to a given displacement. Although the load transfer method was developed for conventional piles, Knellwolf *et al.* (2011) expanded it to include thermal loading and the interaction with the superstructure.

Among the several models that have been proposed to represent the mobilized shaft friction (τ_s) and the base reaction (τ_b) as functions of the element axial displacement (Bohn *et al.,* 2017), the tri-linear curves by Frank and Zhao (1982) have gained widespread adoption due to their simplicity and the limited number of parameters required. In this model (Figure 3), the slopes that define the load transfer curves at the shaft and base of the pile (K_s and K_b, respectively) depend on the pile diameter (D) and the Menard modulus (E_M):

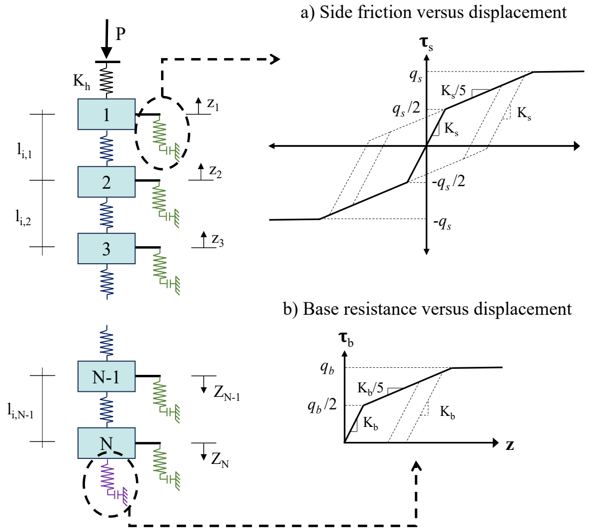
$$K_s = \frac{\alpha_s E_M}{D} \;;\; K_b = \frac{\alpha_b E_M}{D} \tag{1}$$

where α_b and α_s are creep factors that vary by soil type. For granular soils, α_b = 4.8 and α_s = 0.8; for cohesive soils, α_b = 11 and α_s = 2 (Abchir *et al.*, 2016). The slopes, K_s and K_b, remain constant until the mobilized resistance equals half of the ultimate shaft resistance (q_s) or the base bearing capacity (q_b) (Figure 1). q_s and q_b are usually calculated using the total stress (α–method) or the effective stress methods (β–method), depending on the soil type. However, these values can also be determined using the limit pressure (p_l) of a pressuremeter test (PMT) (Burlon *et al.*, 2014), avoiding formulas based on soil strength parameters (*i.e.*, cohesion and friction angle) measured in small undisturbed samples. The corresponding relations are the following:

$$q_b = k_p p_L^* \tag{2}$$

$$q_s = \kappa\, h_i(p_L^*) \tag{3}$$

where k_p is the bearing resistance factor that depends on soil type and pile class, κ is an installation factor that depends on soil type and pile category, and p_L^* is an equivalent net limit pressure. This approach, also known as PMT 2012, is included in in the French standard for pile design according to Eurocode 7 and in the Complementary Technical Standards for the Design and Construction of Foundations of Mexico City (NTCDCC, 2023).


a) Side friction versus displacement

b) Base resistance versus displacement

Figure 3. The load transfer method based on the T-Z function by Frank and Zhao (1982) (Adapted from Knellwolf *et al*., 2011).

3 RELIABILITY ANALYSIS

Several factors cause uncertainty in geomechanical modeling and analysis. Auvinet (2002) classifies the most important ones as follows: (1) spatial variation and scale effect, (2) validity of constitutive laws, (3) validity and accuracy of geomechanical models, and (4) environmental conditions and stresses to be considered in geotechnical analyses. Probability theory has been widely accepted as a tool for representing uncertainty in engineering, as it can be interpreted in terms of both "relative frequency" and "degree of belief". In this framework, the design parameters (*e.g.*, soil resistance, loads) are modeled as random variables with specific probability density functions (PDF) to represent their uncertainties.

Reliability analysis involves determining the probability of failure (or unsatisfactory performance) of a system (*e.g.*, the induced displacement at the top of a pile is greater than the corresponding allowable displacements). If the joint PDF of the design variables $X_1, X_2. \dots, X_n$ is $f_{X_1,X_2.\dots,X_n}(x_1, x_2, \dots, x_n)$, then the probability of failure (p_f) can be determined as:

$$P_f = \int_{[g(x)<0]} \cdots \int f_{X_1,\dots,X_n}(x_1, \dots, x_n)\, dX_1 \dots dX_n \tag{4}$$

where $g(\cdot)$ is a function that determines the behavior or state of the system, such that:

$$\begin{gathered}[g(x_1, \dots, x_n) > 0] = \text{Safety condition} \\ [g(x_1, \dots, x_n) < 0] = \text{Failure condition}\end{gathered} \tag{5}$$

For most practical scenarios, the probability of failure cannot be determined analytically, so it is approximated numerically. A simple approach to evaluate Eq. (4) is to replace the real population of random parameters with a sequence of realizations from the joint PDF until the central tendency, dispersion, and probability density of the results are defined (Auvinet, 2002). In this approach, known as Monte Carlo

Simulations (MCS), the probability of failure is approximated as:

$$P_f = \sum_{i=1}^{N} I\left[g\left(x_{1,i}, \ldots, x_{n,i}\right)\right] \quad (6)$$

where $I[\cdot]$ is a n indicator function equal to 1 if $g(x_1, \ldots, x_n) < 0$. MCS enables the estimation of failure probabilities when complex limit state functions exist for which analytical solutions are unavailable.

4 CASE STUDY

4.1 *Generalities*

In this paper, the reliability analysis of an individual energy pile located in Mexico City is carried out. The foundation element consisted of a concrete pile with a diameter of 1.0 m and a length of 30 m.

4.2 *Characteristics of the study site*

The study site is located in the eastern part of the Transmexican Volcanic Belt, a physiographic province characterized by intense volcanism. The local geology is part of the Las Cruces volcanic sequence. Each volcanic structure produced lava flows and domes that formed the high zones of the range. These zones consist of andesites, dacites, and, to a lesser extent, basalts with calc-alkaline affinities (Osete *et al*., 2000). Based on Mexico City's geotechnical zoning, the stratigraphic profile in the area consists of backfill materials of low compactness, followed by an intercalation of silt and fine to medium grayish sand overlying a thick layer of medium to coarse sand and gravel.

4.3 *Exploratory analysis of geotechnical parameters*

The geotechnical exploratory campaign at the study site consisted of six standard penetration tests (SPTs), with one of them involving the extraction of disturbed samples, nine phicometer tests, and 30 Menard pressuremeter tests (PMT) up to a depth of 45 meters. The groundwater level is below the sounding depth. Additionally, double-needle thermal conductivity tests were performed at thirteen points distributed along an exploration borehole to characterize the thermal properties (*i.e*., thermal conductivity, volumetric heat capacity, and thermal diffusivity) of the materials (Portillo-Arreguín *et al*., 2019). Table 1 presents a summary of the stratigraphy.

Table 1. Site geotechnical model

N	Depth (m)	Description	γ (kN/m^3)
1	0 - 7.5	Backfill material (andesitic and pumice silty sand with gravel and boulders)	17.0
2	7.5 – 21.5	Silty sand with gravel (Blue sands)	20.0
3	21.5 – 27.0	Brown Tuff	20.0
4	27 - 45	Silty sand with gravel	20.0

Note: γ = volumetric weight.

In general, the pressuremeter modulus (E_M) and the limit pressure (p_l) obtained from the 30 PMT exhibited high dispersion, with coefficient of variations as high as 50% (Table 2). Their histogram (Figures 4 and 5) showed asymmetrical distributions with longer right tails. Thus, the lognormal distribution was chosen as a plausible probability density function, as suggested by Fan *et al.* (2014). The distribution parameters were estimated according to the method of moments (Benjamin and Cornell, 1970).

Table 2. Summary statistics of PMT results.

Parameter	Units	n	Min	Max	m	s	COV (%)
Menard modulus	MPa	30	76.6	502.2	180.5	94.2	52.2
Limit pressure	MPa	30	3.1	14.1	6.67	1.99	29.8

Note: PMT = Menard pressuremeter test, n = sample size, Min = minimum, Max = maximum, m = sample mean, s = sample standard deviation, COV = coefficient of variation.

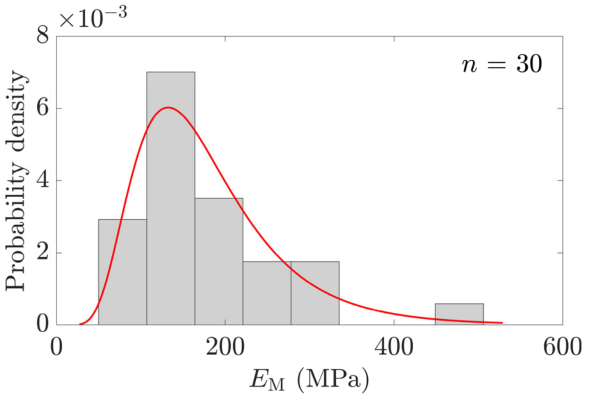


Figure 4. Histogram of Menard's modulus

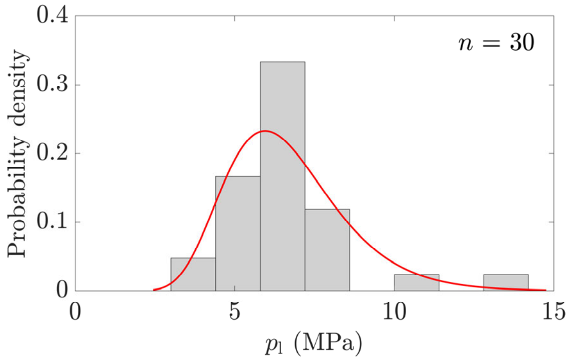


Figure 5. Histogram of the limit pressure modulus

4.4 *Probabilistic analysis*

The probability of failure for different temperature changes (ΔT =-20, 10, 0 °C) was estimated considering only serviceability limit state (SLS) for excessive settlement (Luo and Hu, 2019):

$$[g(x_1, \ldots, x_n)]_{SLS_{settelement}} = s_{ult} - z_1 \quad (7)$$

where s_{ult} is the limiting pile settlement, and z_1 is the displacement at the pile head. These temperatures represent the uniform temperature change imposed on the concrete pile cross-section, simulating the operational conditions induced by the heat carrier fluid within the embedded pipes. While the natural ground temperature is relatively stable, the pile itself undergoes significant temperature variations during the operation of the GSHP. The selected values represent extreme (-20°C) and moderate (-10°C) cooling scenarios as suggested by Rotta-Loria *et al.* (2020), and a reference mechanical load-only case (0°C), providing a comprehensive evaluation of the pile's serviceability under different thermal states. The thermo-mechanical behavior of the energy pile was modeled using the load-transfer method and Frank and Zhao (1982) curves.

The pile was discretized into 30 segments of equal length (1.0 m each) to accurately capture the load-transfer mechanism along the shaft and at the base, regardless of the four identified soil layers. The number of segments directly influences the accuracy of the analysis; a finer discretization provides a better representation of the axial load distribution and soil-structure interaction. A sensitivity analysis confirmed that 30 segments ensured the model's convergence. A limitation of this one-dimensional method is that it does not explicitly capture complex three-dimensional stress interactions or radial heat flow.

The probability of failure was evaluated using 100,000 Monte Carlo simulations. The dead load (L_d), live load (L_l), pile head structure contact stiffness (K_h), Menard modulus (E_M), and limit pressure (p_l) were modeled as independent random variables considering the probability density functions and statistical properties presented in Table 3. This assumption of independence is common in preliminary reliability studies; however, it is acknowledged that correlations may exist (e.g., between E_M and p_l in certain soils), and their investigation is suggested for future research. The PDF and the coefficient of variance (COV) of the mechanical loads (dead and live) and K_h were specified following the recommendations of Ellingwood (1980) and Xiao *et al*. (2016), respectively. The lognormal distribution for PMT parameters was adopted due to its suitability for positively skewed geotechnical data (Fan *et al*., 2014) and its fit to the observed histograms (Figures 2 and 3). The soil parameters were assigned according to the results of the exploratory analysis in section 4.3. A Young's modulus of 20 GPa and a thermal expansion coefficient of $1\text{x}10^{-6}$ /°C were assumed.

Table 3. Variable parameters

Parameter	Model distribution	Units	μ	COV (%)
Dead load	Normal	kN	1980	15
Live load	Gamma	kN	367.7	25
Spring constant	Normal	GPa	1.5	10

Note: μ = mean, COV = coefficient of variation.

5 RESULTS

The displacements obtained showed elongated tails to the right (Figure 6). The maximum displacements for temperature changes of ΔT = 0 °C, ΔT = -10 °C, and ΔT = -20 °C were 40.4 mm, 40.6 mm, and 40.8 mm, respectively. The mean displacements were 15.70 mm, 15.90 mm, and 16.11 mm, respectively. As the temperature decreases, the mean settlement increases.

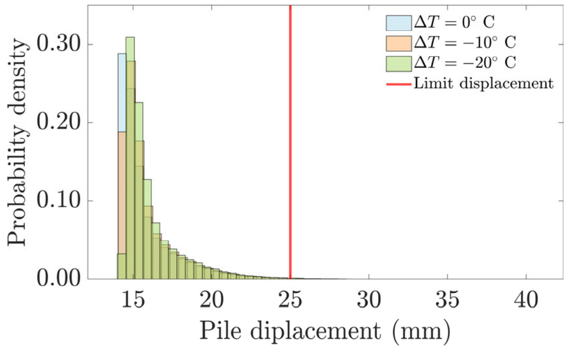


Figure 6. Histogram of the pile displacements for the three temperature changes: ΔT = 0 °C, ΔT = -10 °C, and ΔT = -20 °C.

It is noteworthy that the settlements obtained from a deterministic analysis, using the mean values of all input parameters, were 15.69 mm, 15.90 mm, and 16.11 mm for ΔT = 0 °C, -10 °C, and -20 °C, respectively. These values are virtually identical to the mean of the corresponding probabilistic simulations. This consistency validates the probabilistic models.

To calculate the probability of failure at the three evaluated temperatures, a limiting pile settlement of 25 mm was established, as required for geotechnical Zone 1 according to NTCDCC (2023). Table 4 summarizes the results of the 100,000 simulations. The extreme cooling scenario (ΔT = -20 °C) presented the highest number of simulations that exceeded the limiting pile settlement of 25 mm. The probability of failure (p_f) converged to approximately 0.33% for ΔT = 0 °C, 0.37% for ΔT = -10 °C, and 0.40% for ΔT = -20 °C after 30,000 realizations (Figure 7). Considering the permissible limit of settlement, the probability of failure is small, even in the scenario of extreme cooling. No displacements equal to or greater than 50 mm were found.

Table 4. Probability of failure for different scenarios

	Temperature change		
	-20 °C	-10 °C	0 °C
Simulation in failure region	403	369	330
Probability of failure (%)	0.40	0.37	0.33

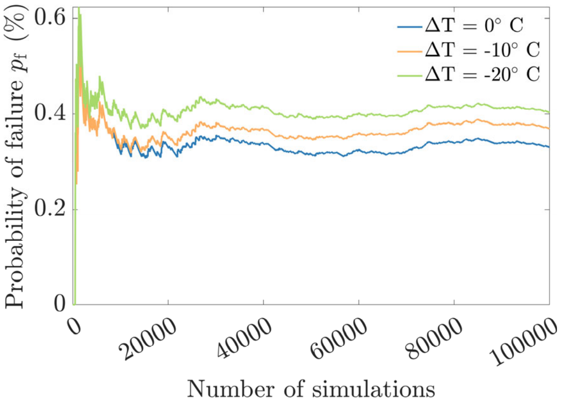


Figure 7. Convergence of the estimates of the probability of failure for a limiting pile settlement of 25 mm.

The primary significance of the probabilistic approach lies in quantifying the uncertainty and the probability of exceeding serviceability limits. For instance, while the relative increase in the mean settlement from the mechanical-load only (0°C) to the extreme cooling (-20°C) scenario is only 2.6%, the probability of unsatisfactory performance (exceeding the 25 mm settlement limit) has a relative increase of 21% (from 0.33% to 0.40%). While the absolute increase in mean settlement due to thermal loads may appear modest, its impact on system reliability is notable, as demonstrated by the 21% increase in the probability of failure. For settlement-sensitive structures, this increase in risk may be unacceptable. Note that the purpose of these analyses is to support the engineering decision-making process, considering the uncertainty in design, construction, and operating conditions, which is crucial for accurately assessing risks and ensuring the reliability of engineering work.

6 CONCLUSIONS

In this paper, the serviceability performance of an individual energy piles in Mexico City subjected to different temperature changes was evaluated using the Monte Carlo Simulation method. The main sources of uncertainty in the thermo-mechanical behavior were considered, including the live and dead loads, the head spring constant, and soil properties. The vertical displacement was estimated using the load-transfer method. Displacement histograms showed that decreasing temperature increases pile displacement, enabling an accurate assessment of its behavior against thermal changes. In no case, the limits permitted by the NTCDCC (2023) were exceeded.

Leveraging the Monte Carlo simulation dataset, a global sensitivity analysis was performed to quantify the relative impact of each uncertain parameter. The analysis yielded a definitive hierarchy: the Menard modulus (E_M) was the predominant driver of displacement variability (correlation coefficient = -0.85), while the live load (L_l) and limit pressure (p_l) had a measurable but lesser effect.

This study lays the groundwork for the probabilistic analysis of energy piles in Mexico. To consolidate this research path and facilitate its practical implementation, future work should focus on: (1) the experimental characterization of the thermal and mechanical properties of typical soils from different geotechnical zones in Mexico, (2) the execution of full-scale load tests on instrumented energy piles to validate numerical and analytical models under local climatic conditions, and (3) the investigation of the long-term impact of thermal cycles (heating and cooling) on the soil-pile interface and the potential evolution of the structural capacity. Addressing these areas will enable the development of specific and reliable design frameworks, promoting the safe and efficient adoption of this sustainable technology in the country.

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