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Improved holding capacity of torpedo anchors induced by thermal consolidation in geotechnical centrifuge models

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Article

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Abstract

Torpedo piles are widely used as anchoring systems in offshore structures due to their simplicity, low cost, and ease of installation. However, their limited vertical holding capacity requires operation under inclined loads to achieve the desired resistance, resulting in undesirable congestion of anchor lines in the production zone. This study investigates thermal consolidation as a strategy to enhance the vertical capacity of torpedo piles by using the pile itself as a heat source. Heating fine-grained soils, such as marine clays, generates a temporary increase in pore pressure which, upon dissipation, induces thermal consolidation around the pile and improves its holding capacity. Geotechnical centrifuge tests were performed to assess the influence of thermal gradients on soil mechanical behavior and soil–torpedo interaction. The results indicate a significant increase in undrained shear strength, as confirmed by T-bar tests, demonstrating the potential of thermal treatment to improve anchoring performance.

1. Introduction

The exploitation of oil in offshore areas has advanced significantly over the past decades, enabling exploration in ultra-deepwater regions. One of the sectors most benefited by this technological progress is the anchoring of offshore structures, particularly permanent facilities such as production platforms. In this context, torpedo piles, widely used in Brazil for temporary moorings, have emerged as an attractive alternative due to their numerous advantages over more conventional anchoring systems worldwide. These advantages include not requiring specialized deployment equipment, installation by self-weight penetration, and low manufacturing cost. However, their primary limitation is the low vertical tensile resistance, which puts them at a disadvantage compared to suction piles — their closest competitors, though suction piles require more complex and costly installation. Consequently, torpedo piles are used under inclined loading in catenary arrangements, unlike the taut-leg systems employed for suction piles. This configuration demands extensive seabed areas to accommodate the mooring lines, increasing operational risks and complicating production and exploration activities, particularly in ultra-deepwater environments.

The seabed along the southern and southeastern Brazilian coast is predominantly composed of low–undrained strength clays, with overconsolidation ratios ranging from lightly overconsolidated to normally consolidated. Conventional solutions to ensure anchoring performance in such conditions typically involve increasing the number or size of anchors. However, these alternatives pose considerable logistical challenges and lead to a greater number of mooring lines, resulting in a more congested and operationally complex subsea environment.

In this scenario, an appealing strategy is to improve the mechanical properties of the marine soil. However, ground improvement techniques commonly applied onshore — such as rigid inclusions, mechanical densification, vacuum application, or electro-osmosis — become impractical at great depths due to operational complexity and high cost.

Conversely, research conducted over the past decades, initially focused on understanding the effects of temperature rise in soils — as in the case of buried power cables or nuclear waste storage — has demonstrated long-term benefits regarding soil compressibility and strength. With the advent of thermally active piles, these studies have gained new relevance, reinforcing the positive effects of controlled thermal elevation under certain conditions.

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Building on these advances, the present study proposes the application of a thermal gradient to induce soil consolidation around torpedo piles, aiming to increase the local undrained shear strength. To validate this approach, geotechnical centrifuge tests were carried out to investigate the mechanisms of soil improvement and quantify the strength gain, since the efficiency of torpedo pile shaft friction is directly linked to this parameter. In these experiments, the torpedo pile itself served as a heat source, activated either after or during pile installation. The physical model was equipped with strategically placed thermocouples and pore pressure transducers, and the undrained shear strength was evaluated using four T-bar tests conducted simultaneously at varying distances from the heat source. This setup allowed assessment of the thermal propagation zone and the resulting strength improvement.

The earliest studies on the effect of temperature on soils were conducted by Campanella & Mitchell (1968), who observed that clayey soils responded differently to heating–cooling cycles depending on their stress history. Normally consolidated or lightly overconsolidated clays exhibited plastic volumetric contraction, whereas heavily overconsolidated clays displayed volumetric expansion. Under rapid heating, these volumetric tendencies were reflected in the development of excess pore pressure — positive for normally consolidated soils and negative for heavily overconsolidated soils.

Subsequent studies (Delage et al., 2000; Houston et al., 1985; Huancollo et al., 2023; Maghsoodi et al., 2020; Samarakoon et al., 2019) demonstrated significant strength gains and reduced compressibility, highlighting the potential of thermal consolidation techniques. Ghaaowd et al. (2022) and Ghaaowd & McCartney (2018) conducted centrifuge tests and observed an initial increase in pore pressure during heating, followed by dissipation once steady-state heat flow was established. Other researchers (Abuel-Naga et al., 2007; Trani et al., 2008) reported that pore pressures returned to negative values in heavily overconsolidated clays.

Several authors have also proposed analytical and numerical solutions for the consolidation problem around a point heat source in saturated soil masses (Booker & Savvidou, 1984; Chaudhry et al., 2019; Savvidou & Booker, 1989), showing good agreement with experimental results. More recently, Huancollo et al. (2023) and Reis et al. (2023) performed temperature-controlled triaxial tests and concluded that rapid undrained heating, followed by consolidation and subsequent cooling, leads to a substantial increase in the undrained shear strength of plastic clays, along with a marked reduction in axial strain at failure.

2. Materials and methods

The tests were carried out in a cylindrical container with an internal diameter of 464 mm and a height of 500 mm (Figure 1). To monitor the consolidation process, three pore pressure transducers (PP) were installed along the wall, as well as two laser displacement sensors to measure settlements during model preparation.

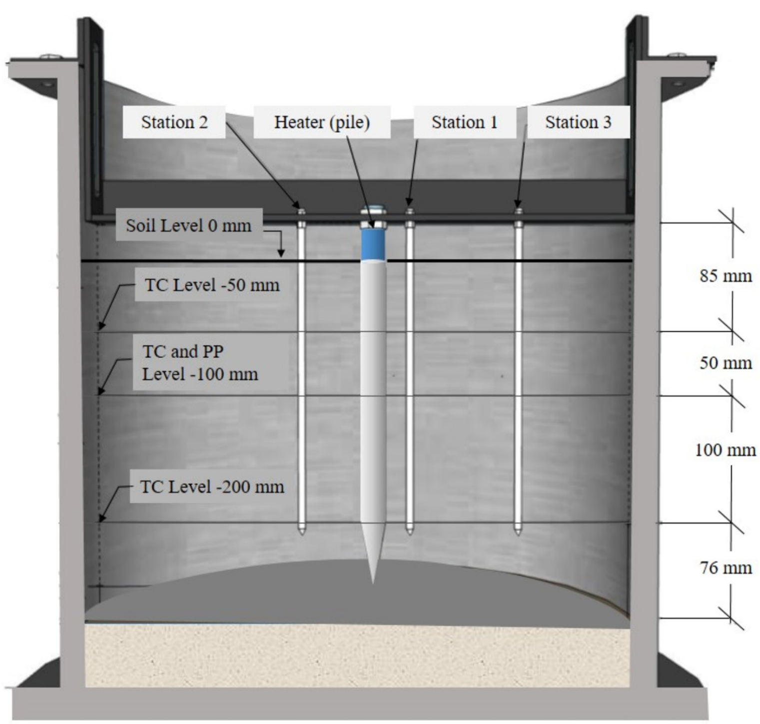

Figure 1. General view of the model (TC: Thermal Couple; PP: Pore Pressure Transducer).

The torpedo pile used in the experiment was made of aluminum, measuring 250 mm in length and 19 mm in external diameter. A 750 W, 200 mm-long electric heating element was installed inside the pile.

Three monitoring stations were positioned at distances of 30, 60, and 120 mm from the torpedo pile to record both temperature variation and pore pressure during the heating process. Thermocouples and pore pressure transducers were installed at these stations to perform the measurements.

The thermocouples were placed at depths of 50, 100, and 200 mm within each station. Pore pressure transducers were installed at Stations 2 and 3 (located 60 mm and 120 mm from the heat source) at a depth of 100 mm, as shown in Figure 2.

To evaluate the undrained shear strength during centrifuge testing, T-bar penetrometers were used. Since one objective of this study was to analyze strength variation as a function of distance from the heat source, four T-bar tests were performed simultaneously. For this purpose, a specific installation system was developed in which each T-bar was positioned at a different distance from the torpedo pile (Figure 3). The selected distances corresponded to 2, 3, 4, and 8 times the pile diameter.

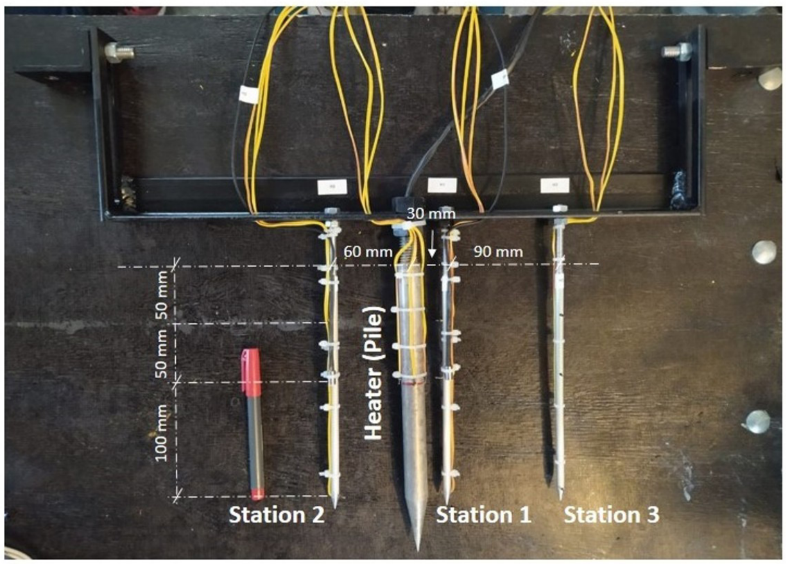

Figure 2. Instrumented stations.

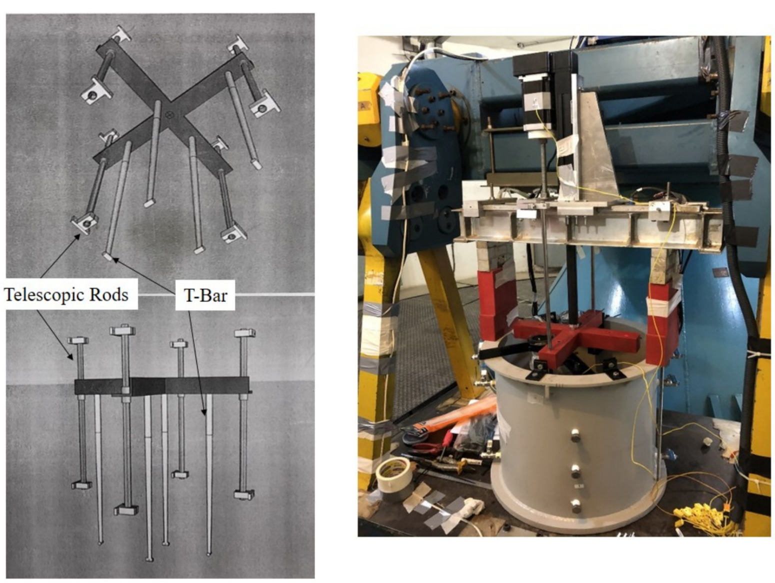

Figure 3. T-Bars installation device.

Table 1. Data from soil layers during 1G consolidation.

Layer	Before mechanical consolidation			After mechanical consolidation		
Test E1						
	e	***ρ* (g/cm^3)**	***w* (%)**	***e***	***ρ* (g/cm^3)**	***w* (%)**
Layer 1	1.81	1.58	67.5	1.45	1.66	53.9
Layer 2	1.83	1.57	68.3	1.25	1.72	46.0
Layer 3	1.85	1.57	69.2	1.18	1.74	43.7
Layer 4	1.85	1.55	67.0	1.14	1.73	40.3
Weighted mean	1.83	1.56	68.0	1.25	1.71	45.9
Test E2						
	e	***ρ* (g/cm^3)**	***w* (%)**	***e***	***ρ* (g/cm^3)**	***w* (%)**
Layer 1	1.76	1.60	67.7	1.48	1.67	57.2
Layer 2	1.84	1.57	69.1	1.32	1.70	49.6
Layer 3	1.81	1.58	68.1	1.21	1.74	45.5
Layer 4	1.80	1.59	68.8	1.16	1.76	44.6
Weighted mean	1.80	1.59	68.5	1.29	1.72	49.1
Test E3						
	e	***ρ* (g/cm^3)**	***w* (%)**	***e***	***ρ* (g/cm^3)**	***w* (%)**
Layer 1	1.76	1.61	68.3	1.43	1.69	55.6
Layer 2	1.86	1.56	69.0	1.36	1.68	49.8
Layer 3	1.77	1.60	67.2	1.16	1.76	44.2
Layer 4	1.81	1.59	68.9	1.16	1.76	44.1
Weighted mean	1.80	1.59	68.4	1.28	1.72	48.4

2.1 Model preparation

The soil used in the tests consisted of a mixture of 40% kaolin and 60% metakaolin, initially prepared at a water content 1.5 times its liquid limit. After homogenization, the mixture was composed of 63% silt, 35.5% clay, and exhibited a plasticity index (*PI*) of 19%. To accelerate consolidation during centrifuge testing, the soil underwent prior mechanical consolidation in a large-scale oedometer.

The prepared soil was placed in the cylindrical container in sufficient quantity to form, after consolidation, a 70 mm-thick layer. This layer was compacted under a stress slightly higher than the equivalent geostatic stress expected at that depth in the centrifuge. The same procedure was repeated to form three additional layers, producing a 280 mm-high soil column. The final average void ratio after consolidation varied between 1.25 and 1.29, resulting in a degree of saturation of at least 97%. Table 1 includes a summary of the parameters before and after mechanical consolidation for the reference test, E1 as well as the heated tests E2 and E3, respectively. This arrangement was designed to achieve an average overconsolidation ratio (*OCR*) of 2.5 during centrifuge flight, as illustrated in Figure 4.

2.2 Centrifuge tests

After initial one-dimensional consolidation in the large scale oedometer, the pile — which also served as a heat source — and the instrumentation rods were statically inserted into the soil. The T-bars penetration system was then positioned inside the container, and the model was reconsolidated in the geotechnical centrifuge under an acceleration of 20*g*.

Three centrifuge tests were performed. The first, labeled E1, served as a reference test conducted at ambient temperature. The subsequent tests, E2 and E3, involved heating the pile to 65 °C and 45 °C, respectively, followed by natural cooling. The different stages of the geotechnical centrifuge tests are described in Table 2.

Table 2. Stages followed for the centrifuge tests.

Test stage	Description	Environment
1	Soil preparation and mechanical consolidation in 4 layers	Outside centrifuge
2	Installation of the pile and instrumented stations	
3	Self-weight consolidation at 20*g*	During centrifuge operation
4	Heating the pile torpedo (Tests E 2 and E3 only)	
5	Cooling the pile torpedo (Tests E2 and E3 only)	
6	T-bar tests at 20*g*	

In Test E1, once 20*g* acceleration was achieved and instrument readings confirmed stabilization, the T-bar tests were initiated. Penetration was performed at a rate of 20 mm/s as proposed by Stewart & Randolph (1994) to ensure undrained conditions during the four simultaneous tests, each located at a different distance from the pile, as detailed before.

3. Results and discussion

3.1 Reference Test E1

Although identical results were expected from the four penetrometers in Test E1, natural soil variability and boundary effects led to slight differences. Therefore, the average of the four measurements was adopted as a baseline for comparison with Tests E2 and E3. Figure 5 presents the undrained shear strength (S_u) profiles and the average reference curve.

Tests E2 and E3 followed procedures similar to E1 but included the thermal consolidation phase as already shown in Table 2. In these tests, the pile was heated to 65 °C (E2) and 45 °C (E3) and after the initial pore pressure increase caused by heating and subsequent stabilization, the system was allowed to cool naturally. The temporal evolution of temperature at each monitoring station, normalized by distance from the pile, is shown in Figure 6.

Pore pressure transducers were installed at Monitoring Stations 1 and 2, each at a depth of 100 mm (model scale).

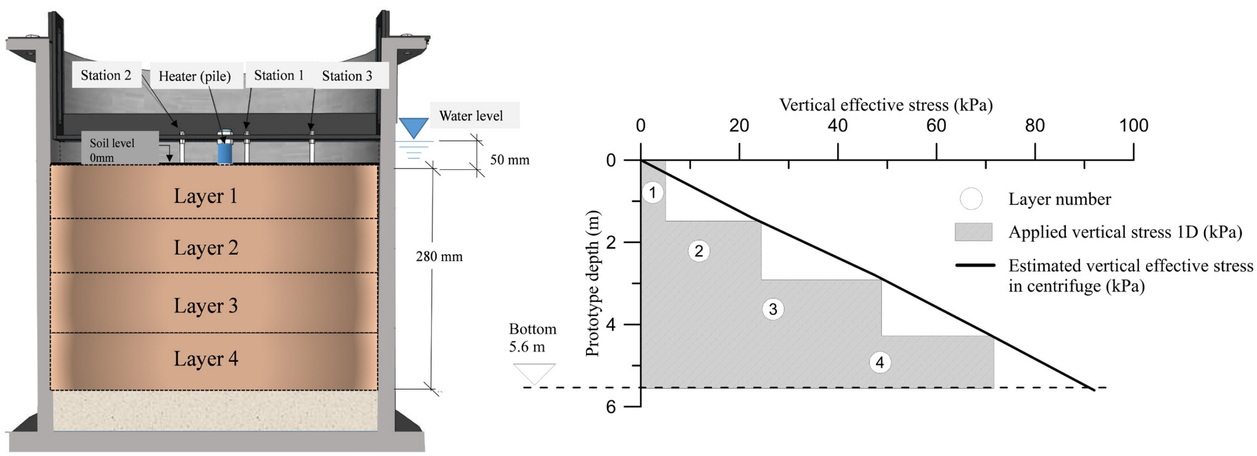

Figure 4. Consolidation scheme.

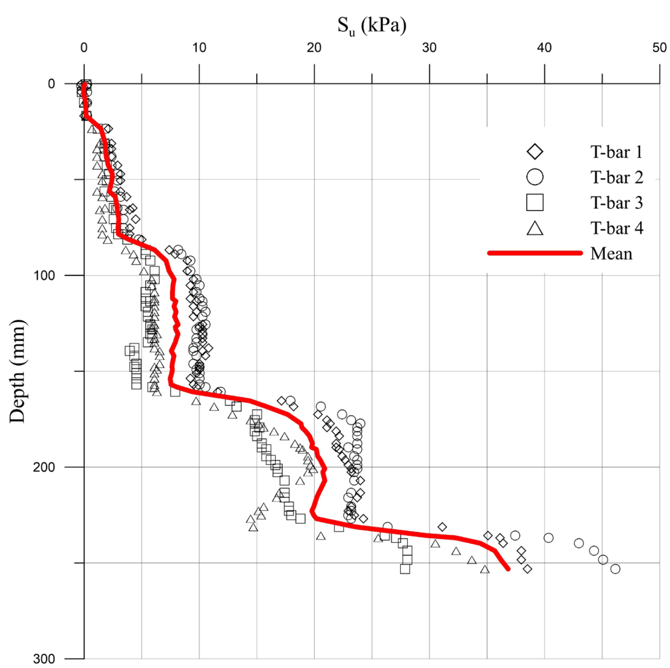

Figure 5. Undrained strength profile for the test E1.

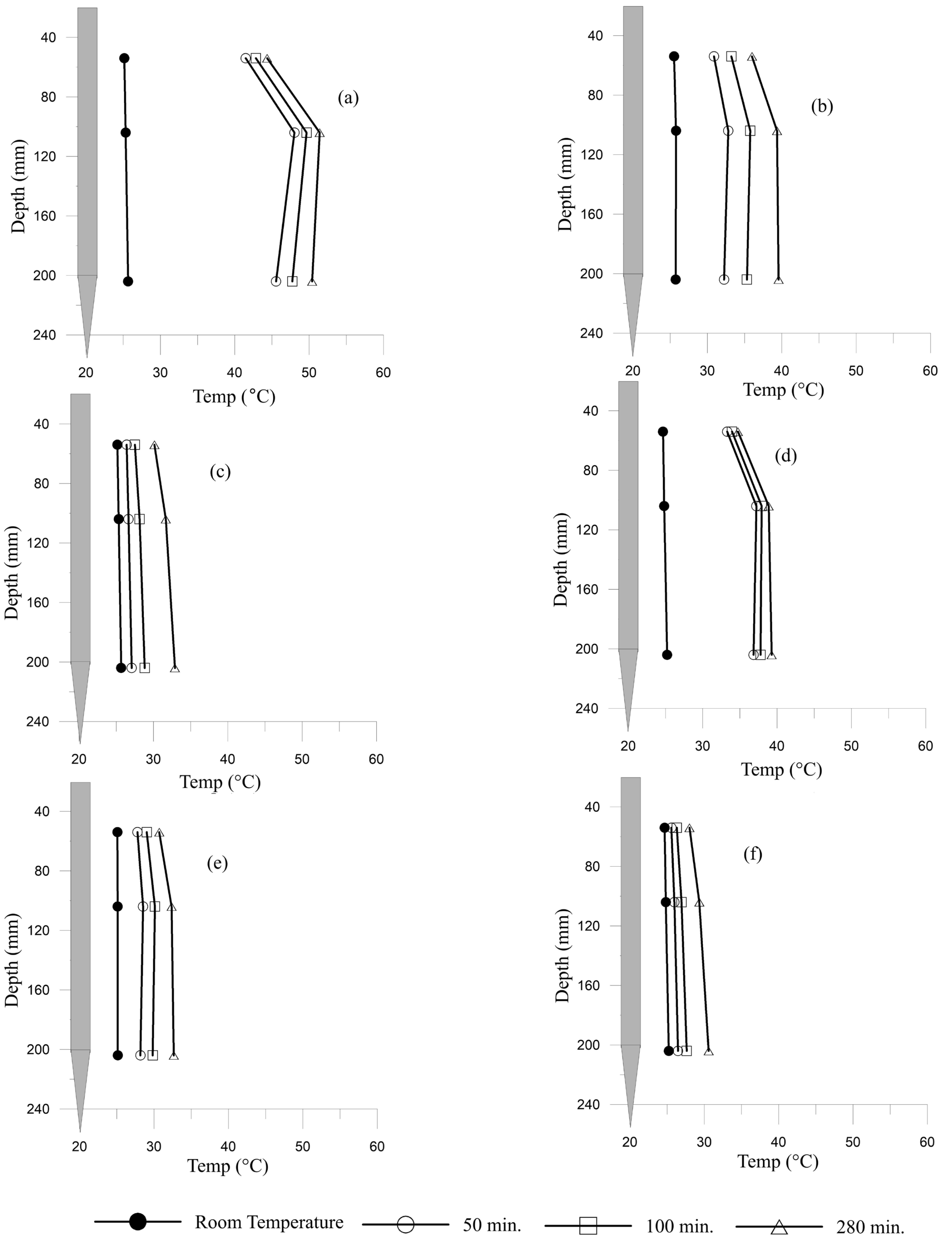

Figure 6. Temperature evolution with time recorded by the monitoring stations. (a) Test E2, Station 1; (b) Test E2, Station 2; (c) Test E2, Station 3; (d) Test E3, Station 1; (e) Test E3, Station 2; (f) Test E3, Station 3.

The pore pressure variations induced by heating are presented in Figure 7, showing an initial rise during heating followed by dissipation as thermal consolidation progressed. After cooling, a secondary pore pressure increase was observed — a typical response in lightly overconsolidated soils.

The Su profile from the reference test indicated that the soil strata were distinctly defined, which exhibited clear strength plateaus at each layer. To allow a direct comparison of undrained shear strength across the tests, each of the four layers was analyzed separately by calculating the average strength measured by the T-bars in E2 and E3 and comparing these with the corresponding average from E1 (Figure 8). Additionally, it was considered useful to report the overall mean strength ratio, determined from the average response of the four T-bars within each layer.

For T-bars 1 to 4 in test E2, which were heated to 65 °C and then cooled to room temperature, the results indicated substantial increases in undrained shear strength across all measurement points. The most pronounced improvement occurred for T-bar 1, where strength in the second soil layer reached approximately 2.8 times that of the reference test. In contrast, the layer between 210 mm and 280 mm depth—being farther from the heat source — showed more moderate gains for all T-bars. Similar to the trend in E3, T-bar 1 displayed its largest strength increase in the second layer, around 1.8 times the reference value, whereas the uppermost layer exhibited only minor improvements for the other T-bars. This limited enhancement near the surface is attributed to heat transfer dominated by convection, which is influenced by both exposure time and wind effects during centrifuge operation.

The undrained strength profiles confirm that the results of E3 (heated to 45 °C) closely follow those of E2, although layer-by-layer averages reveal smaller, yet still significant, gains relative to the reference test. Statistical analysis of all measurement points highlights these differences: in E2, roughly 40% of the undrained strength values for T-bar 1 were three to four times greater than the reference and 1.2 to 2.8 times higher than the other T-bars. For T-bar 2, strength values ranged from 1.1 to three times the reference, with 40% exceeding twice the baseline. In contrast, for T-bars 3 and 4, gains above twofold were less frequent, with 80% of results falling between 1.1 and two times the reference strength.

4. Conclusion

The phenomenon of thermal consolidation in soft soils, associated with temperature variation, has been extensively demonstrated over the past decade through specialized laboratory tests such as triaxial and oedometer experiments. In this study, geotechnical centrifuge modeling was employed to investigate the impact of temperature increase on enhancing the capacity of torpedo anchors, whose performance is directly governed by the undrained shear strength of the surrounding soil.

To assess the feasibility of applying this technique to offshore anchoring systems, three centrifuge tests were conducted: one reference test at ambient temperature and two thermal consolidation tests at 65 °C and 45 °C, respectively.

Both heated tests showed a substantial improvement in soil strength. The most significant results were obtained in Test E2 at 65 °C, where the increase in undrained shear strength was more pronounced. However, even in Test E3, performed at the lower temperature, strength gains of up to 200% were recorded in regions closest to the heat source.

The results confirm the effectiveness of the technique and its potential applicability in deepwater environments, where the torpedo pile itself can act as a heat source. This approach may reduce the total number of piles required in anchoring systems and enable vertical alignment of mooring lines, thereby mitigating subsea congestion — one of the major operational challenges in oil exploration and production activities.

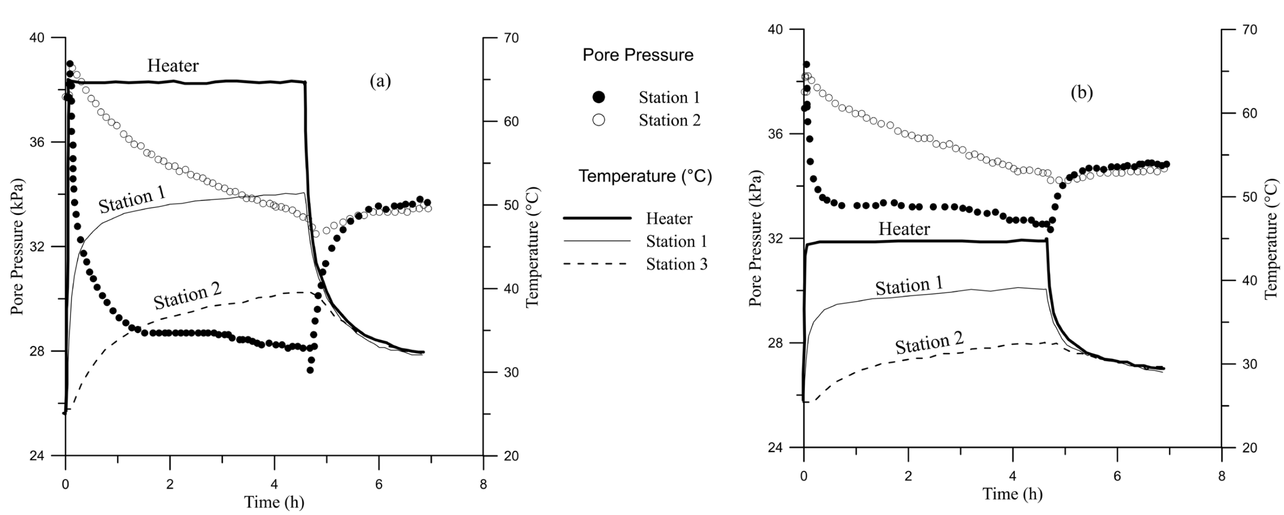

Figure 7. Pore pressure induced by the increase in temperature followed by cooling. (a) Test E2; (b) Test E3.

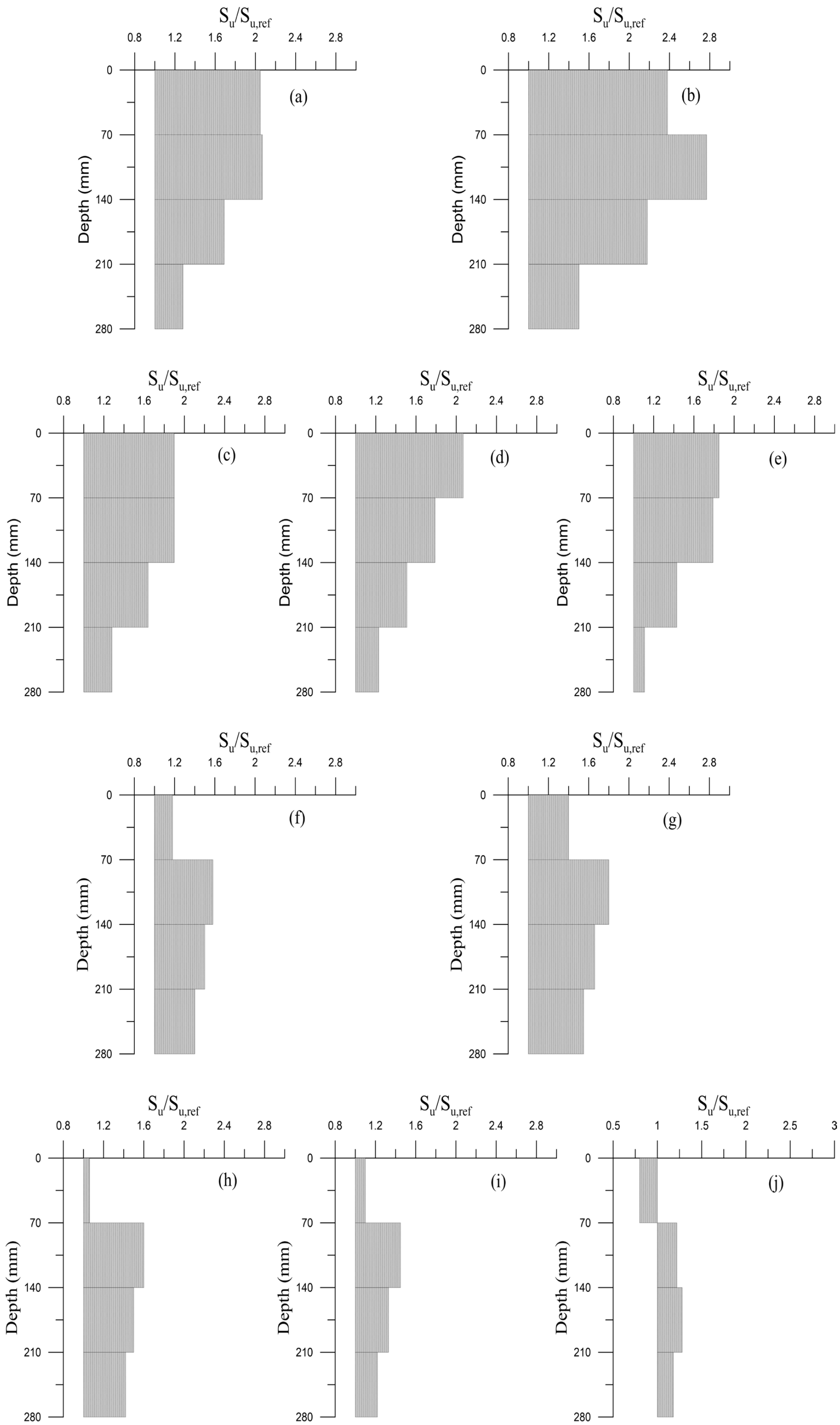

Figure 8. Gain in undrained strength with prototype depth, after thermal consolidation given by the ratio $S_u/S_{u,ref}$. (a) Test E2, overall mean; (b) Test E2, T-bar1; (c) Test E2, T-bar2; (d) Test E2, T-bar3; (e) Test E2, T-bar4; (f) Test E3, overall mean; (g) Test E3, T-bar1; (h) Test E3, T-bar2; (i) Test E3, T-bar3; (j) Test E3, T-bar4.

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Declaration of interest

The authors declare that they have no conflicts of interest related to this work. All co-authors have reviewed and approved the content of the manuscript, and no financial or personal interests have influenced the results or conclusions presented.

Authors' contributions

Marina de Souza Ferreira: investigation, writing – original draft, data curation, conceptualization. Fernando Saboya Júnior: conceptualization, formal analysis, validation, investigation. Sérgio Tibana: conceptualization, project administration, supervision, resources, investigation. Rodrigo Martins Reis: investigation, methodology. Cassia Maria de Assis Rangel Melo: writing – review & editing, visualization. Ricardo Garske Borges: funding acquisition, conceptualization.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

e	Void ratio
g	Earth´s gravity acceleration
w	Moisture content
IP	Plasticity index
NA	Normally consolidated
OC	Over consolidated
OCR	Over consolidation ratio
PP	Pore pressure transducer
S_u	Undrained strength
$S_{u,ref}$	Reference undrained strength (test E1)
TC	Thermal Couple
ρ	Specific weight

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