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The interface failure mechanism of energy piles

Le mécanisme de rupture à l'interface des pieux énergétiques

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ABSTRACT: The interface failure mechanism of energy piles can be described as a shear band characterised by large, localised strains detached from the surrounding soil behaving under oedometric conditions. Thermal cycles are a new player in energy piles foundations that can affect the behaviour at the pile-soil interface. In this study, the failure mechanism at the pile-soil interface subjected to cyclic thermal loads was investigated from experimental and constitutive perspectives. The volumetric response of the soil (studied through oedometric tests) and the shear response of the soil-concrete interface (analysed with constant normal stiffness (CNS) direct shear tests) to cyclic thermal loads were combined to describe and better understand the failure mechanism at the pile-soil interface. Temperature variations for practical ranges of energy piles (thermal cycles between 10 and 40 °C) showed negligible effects. The effectiveness of using an isothermal model was demonstrated by modelling the results of the tests subjected to thermal cycles. In addition, the proposed constitutive model has the advantage of being developed under the framework of the Mohr-Coulomb elastoplastic models. This makes it more attractive and usable for engineering analysis.

RÉSUMÉ : Le mécanisme de rupture de l'interface des pieux énergétiques peut être décrit comme une bande de cisaillement caractérisée par de grandes déformations localisées, détachées du sol environnant et se comportant dans des conditions oedométriques. Les cycles thermiques sont un nouvel acteur dans les fondations de pieux énergétiques qui peuvent affecter le comportement à l'interface pieu-sol. Dans cette étude, le mécanisme de rupture à l'interface pieu-sol soumis à des charges thermiques cycliques a été étudié d'un point de vue expérimental et constitutif. La réponse volumétrique du sol (étudiée par des essais oedométriques) et la réponse en cisaillement de l'interface sol-béton (analysée par des essais de cisaillement direct à rigidité normale constante) aux charges thermiques cycliques ont été combinées pour décrire et mieux comprendre le mécanisme de rupture à l'interface pieu-sol. Les variations de température pour des valeurs pratiques de pieux énergétiques (cycles thermiques entre 10 et 40 °C) ont montré des effets négligeables. L'efficacité de l'utilisation d'un modèle isotherme a été démontrée en modélisant les résultats des essais soumis à des cycles thermiques. En outre, le modèle constitutif proposé présente l'avantage d'être développé dans le cadre des modèles élastoplastiques de Mohr-Coulomb. Cela le rend plus attractif et utilisable pour l'analyse d'ingénierie.

KEYWORDS: energy piles, soil-concrete interface, thermomechanical behaviour, laboratory testing, cyclic load.

1 INTRODUCTION

Understanding the soil-structure interface behaviour is critical for determining the load-transfer for foundations such as axially loaded piles. The shaft resistance represents the main contribution in assessing the axial capacity of energy pile. In energy pile foundations, the response of an energy pile–soil interface is influenced by seasonal and daily cyclic thermal variations. Such physical processes should be considered in the analysis of the behaviour of soils and soil-concrete interfaces.

With regard to fine-grained soil behaviour, for which a relatively high sensitivity to temperature variations has been historically observed, extensive studies have been performed on clay for different thermal paths (Hueckel & Pellegrini, 1989; Hueckel & Baldi, 1990; Robinet et al., 1997; Burghignoli et al., 2000; Graham et al., 2001; Cekerevac & Laloui, 2004; Ghahremannejad, 2003; Yavari et al., 2016; Li et al., 2019; Maghsoodi et al., 2020) and, only recently, on clay-structure interfaces (Di Donna et al., 2016; Yavari et al., 2016; Li et al., 2019; Yazdani et al., 2019; Maghsoodi et al., 2020). The results indicate that the temperature has a negligible influence on the angle of the shear strength. In addition, the new results presented in Ravera et al. (2020) highlighted a negligible variation of the normal stress acting on the pile shaft in relation to thermal actions based on tests in which both CNS conditions and cyclic thermal loads are applied together. Therefore, this paper presents a theoretical interpretation of the experimental results of Ravera et al. (2020) and a constitutive study to investigate the shear response of the soil-structure interface subjected to cyclic thermal loading. The tests presented in the following refers to direct shear tests as representative of the mechanism that occurs at the pile-soil interface (Boulon & Foray, 1986). The interpretation of the direct shear test was based on the idealisation of the interface as a surface. Originally proposed by Boulon (1989) for conventional piles, it is herein proposed in the context of energy piles. The soil sample is schematically decomposed in a sheared interface, and an oedometric sample that acts as a restraining elastic medium (Boulon, 1989; Ghionna & Mortara, 2002; Pra-ai & Boulon, 2017). Experimental data from oedometric tests and constant normal stiffness direct shear tests, where the soil and the soil-structure interface have been subjected to thermal cycles, are presented first, and essential features of the observed behaviour are discussed. Finally, the basic failure phenomenon of the soil-structure interface of energy foundations is described by an elastoplastic constitutive model.

2 RHEOLOGICAL EVIDENCES

The experimental program comprised cyclic thermal tests under a constant vertical effective stress in oedometric conditions and CNS direct shear tests, where the soil-concrete interface was subjected to thermal cycles. It was necessary for the volumetric and shear responses to be individually studied to obtain an understanding of the coupled behaviour. In this study the main specifications and results are presented to support the understanding of the interface failure mechanism and the constitutive model.

2.1 *Experimental setup, materials, and methods*

The thermomechanical behaviour of a clayey soil subjected to cyclic thermal loading was analysed using oedometric cells developed by Di Donna and Laloui (2015). This allowed to understand the influence of the volumetric behaviour of the soil on the interface response. Soil-concrete interface tests at constant normal stiffness to evaluate the effects of cyclic thermal loads on shear strength were carried out using a direct shear device, recently modified by Ravera et al. (2020) to allow the application of heating and cooling cycles. The setups are shown in Figure 1.

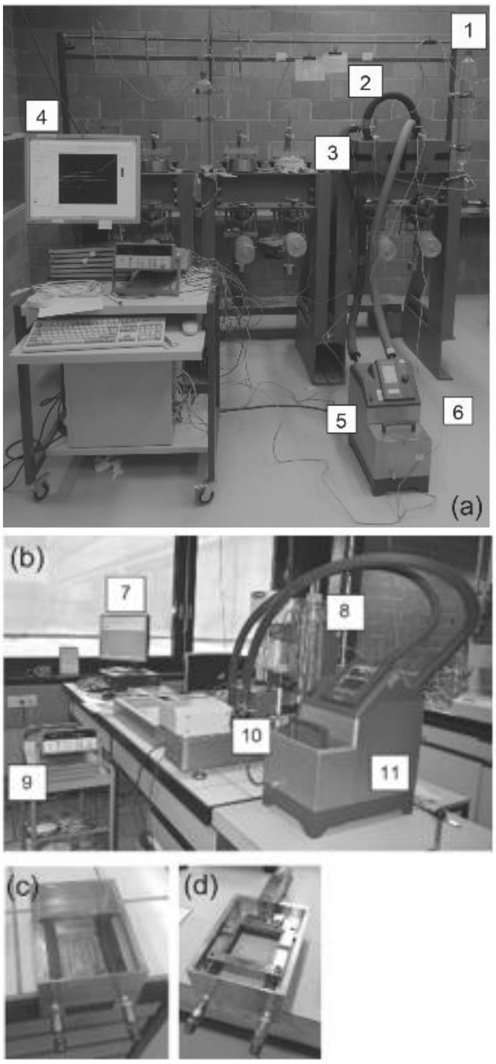


Figure 1. (a) Global view of the temperature-controlled oedometric cell. (b)(c)(d) Direct shear device and details of the modified shear box. (1, 8: water supply systems; 2: thermal hydraulic system; 3, 10: insulation; 4, 7, 9: software control and datalogger thermocouples; 5, 11: thermal bath; 6: thermocouples) (after Ravera et al. (2020)).

A clayey soil was used in the experiments; the particle size distribution and the mineralogical composition are shown and described in Figure 2.

The same method of preparation of the specimens, i.e., by static compaction, was used for the oedometric tests and the direct shear tests. The choice was motivated by the objective of having identical initial conditions to observe the thermal and mechanical effects and their combination in the same experimental campaign. Concrete was the interface material in the direct shear tests.

The oedometric test procedure involved the imposition of a mechanical load, followed by the imposition of cyclic thermal loads. For the direct shear tests, after the consolidation phase, the thermal cycles were performed under constant normal stiffness conditions. Monotonic shearing was performed at ambient temperature after the application of the cyclic thermal loads. The operating ranges of the mechanical load and thermal cycles applied to the specimens were defined on representative values for the application of energy piles, simulating the soil conditions in situ when an energy pile is in operation. Table 1 and 2 summarised the test variables and the initial condition of the test presented in this paper which are considered the most representative of the behaviour at the interface of an energy pile.

Additional detailed information on the experimental setup, materials and methods can be found in Ravera et al. (2020).

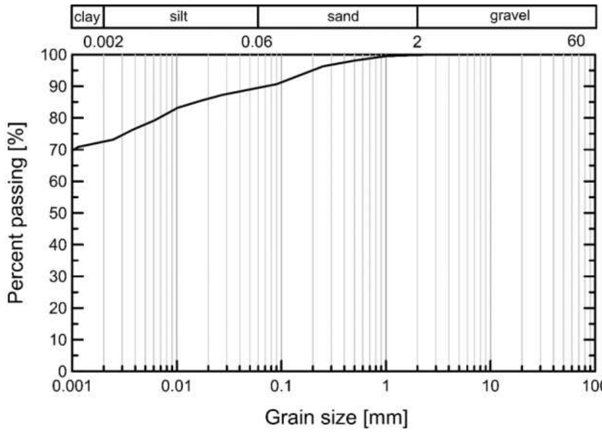


Figure 2. Particle size distribution of the clayey soil used in the experiments. Atterberg's limits: liquid limit 56 %, plastic limit 32%, plasticity index 24%. Mineralogical composition: 77% illite, 10% kaolinite, 12% calcite, and traces of feldspar and quartz (after Ravera et al. (2020)).

Table 1. Thermal cycle oedometer: test variables and initial conditions of the sample.

Test variables				
OCR	σ_n [kPa]	Heating rate [°C/h]	ΔT[°C]	N° cycles
1	125	2	+20/-10	5
Initial conditions				
w[%]	e[-]	ρ_s[Mg/m^3]	ρ[Mg/m^3]	
35.7	1.410	2.65	1.49	

2.2 *Observed behaviour*

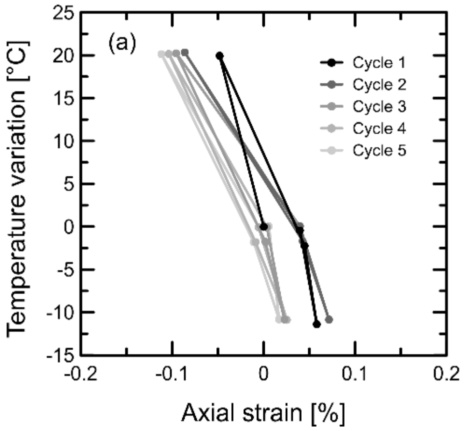
An interpretation procedure based on mechanical analogy was adopted for the analysis of the results of the study on thermovolumetric behaviour with the advantage of analysing the effects of mechanical and thermal loads for a design of energy piles according to the classical geotechnical analysis scheme. Indeed, one of the problems hindering the extension of this technology from academia to industry at present is the lack of standards and interpretation procedures for laboratory tests involving temperature. More details are presented by Ravera et al. (2020). An almost reversible behaviour is observed in Figure 3(a). Very low residual strain changes are noted in relation to cyclic thermal changes. The temperature cycles therefore seem not to alter the boundary conditions of the interface zone.

The study of the pile-soil interface behaviour was carried out to understand the probability of degradation of the shear strength (i.e., reduction of normal stress) under cyclic thermal loads. The interface test results after the application of heating-cooling cycles under CNS conditions compared to the conventional test results do not show a significant difference in the shear response behaviour of the interface (Figure 3(b)). A negligible effect of the application of thermal load on the shear stress in the shear phase can be considered. Furthermore, based on the observations of Ravera et al. (2020), no significant changes in the volume and thus in the effective normal stress during a thermal cycle were shown. The probability of degradation of the shear strength of piles when subjected to a cyclic thermal load is therefore minimal and changes in the failure envelope are negligible.

Table 2. Direct shear test: test variables and initial conditions of the samples.

Test variables					
OCR	$\sigma_{n,i}$ [kPa]	Shear condition [kPa/mm]	Shearing rate [mm/min]	ΔT[°C]	N° cycles
1	125	CNS K=200	0.003	-	-
1	125	CNS K=200	0.003	+20/-10	3

Initial conditions				
	w[%]	e[-]	ρ_s[Mg/m^3]	ρ[Mg/m^3]
Conventional	36.2	1.400	2.65	1.50
Thermal	34.6	1.400	2.65	1.49



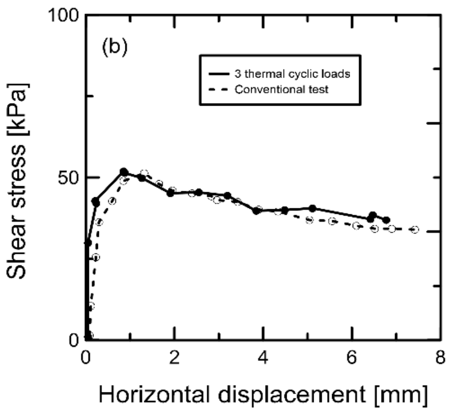


Figure 3. Results of the oedometric (a) and direct shear (b) tests with applied thermal cyclic loads (after Ravera et al. (2020)).

Some considerations for the analysis and design of energy piles can be made on the basis of these results. The results show an almost reversible volumetric behaviour and negligible effects on the shear strength of the soil-concrete interface towards cyclic thermal loads from a practical point of view. Therefore, when using simplified analysis methods in the preliminary design stages neglecting temperature sensitivity can be justified.

3 ELASTOPLASTIC INTERFACE CONSTITUTIVE MODEL

In the following an interface model for simulating the failure mechanism along energy piles is presented. A temperature independence was highlighted by the experimental results discussed in the previous section. Therefore, the effectiveness of using an isothermal approach to model the results of the tests subjected to thermal cycles is illustrated.

3.1 *Model features*

Equivalent continuum theory is not applicable to mechanisms involving large relative displacements such as at interfaces. A pragmatic approach (Boulon, 1989) consists of replacing the interface by a zone of zero thickness where kinematic discontinuities occur. This representation can be used to model the complex phenomena occurring between the two boundaries of a shear band within the soil adjacent to a structure. The model is then formulated in terms of stresses and displacements and the interface is idealised as a continuum surface subjected to kinematic discontinuities. It is a two-dimensional model that has the characteristics of a Mohr Coulomb model. The main features of the model are (i) a linear elastic behaviour, where the normal K_n and shear stiffness K_s link stresses to displacements, normal and shear respectively, in a decoupled manner; (ii) a Mohr Coulomb plastic surface: (iii) a non-associated flow rule and (iv) a hyperbolic hardening rule. Equations (1) and (2) represent the plastic surface and plastic potential of the model:

$$f(\sigma_n', \tau, k) = \tau - k\sigma_n' \quad (1)$$

$$g(\sigma') = \tau - \mu\sigma_n' ln\frac{\sigma_n'}{\sigma_r'} \quad (2)$$

where the plastic potential is obtained from a stress-dilatancy relationship. τ is the shear stress, σ_n' is the normal stress, σ_r' is an arbitrary variable, k is the stress ratio and μ is the shear coefficient. The model was used to reproduce the behaviour of interface where no dilation was observed. Equation (3) is the hyperbolic expression that was used for the hardening function:

$$\frac{k}{k_p} = \frac{w^p}{a + w^p} \quad (3)$$

where the stiffness degradation is described through a relationship between the stress ratio k and the shear displacements w^p. The model is therefore characterised by five parameters, which are shown in Table 3.

Table 3. Parameters of the model.

Elastic parameters	
Normal stiffness [kPa/m]	K_n
Shear stiffness [kPa/m]	K_s
Plastic parameters	
Shear coefficient	μ
Limiting value of stress ratio	k_p
Soil constant	a

3.2 *Model application*

Figure 4 shows the comparison between an experimental test carried out on a soil-concrete interface in constant normal stiffness conditions. The initial normal stress was 125 kPa and the sample was subjected to three thermal cycles. The development of the shear stress is well interpreted by the model. In Figure 4(b) the experimental and predicted stress path are reported, the reduction in normal stress caused by the application of the constant normal stiffness condition which is considered the most appropriate condition to reproduce the behaviour at pile-soil interface is well reproduced providing important information about the evolution of the process in the pre-failure phase. The effectiveness of using an isothermal approach to model the results of the tests subjected to thermal cycles is illustrated.

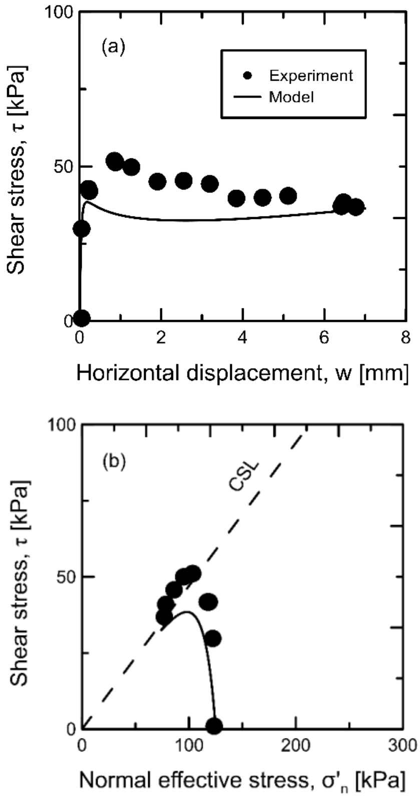


Figure 4. Comparisons between the experimental results and the model predictions. (a) stress-strain behaviour; (b) Mohr plane: load paths and failure behaviour.

4 CONCLUSION

The probability of degradation of the shear strength of the piles, when subjected to cyclic thermal loading, is minimal and the changes in the failure envelope are negligible.

The experimental results indicated that the interface behaviour for the energy pile when a cyclic temperature variation was applied (for temperatures above zero degrees) was not different from that of the conventional pile. This has led to the development and validation of a mathematical model for energy pile-soil interface with the same formal structure as the constitutive models normally used for conventional piles. The proposed constitutive model has the advantage of being developed under the framework of the Mohr-Coulomb elastoplastic models which makes it more attractive and usable for engineering analysis.

5 ACKNOWLEDGMENTS

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6 REFERENCES

Boulon, M., and Foray, P. 1986. Physical and numerical simulation of lateral shaft friction along offshore piles in sand. In Proc., 3rd Int. Conf. on Numerical methods in offshore piling (pp. 127-147). Nantes, France: Institut Francais du Petrol.

Boulon, M. 1989. Basic features of soil structure interface behaviour. Computers and Geotechnics, **7**(1-2), 115-131.

Burghignoli, A., Desideri, A., and Miliziano, S. 2000. A laboratory study on the thermomechanical behaviour of clayey soils. Canadian Geotechnical Journal, **37**(4), 764-780.

Cekerevac, C., and Laloui, L. 2004. Experimental study of thermal effects on the mechanical behaviour of a clay. International journal for numerical and analytical methods in geomechanics, **28**(3), 209-228.

Di Donna, A., and Laloui, L. 2015. Response of soil subjected to thermal cyclic loading: experimental and constitutive study. Engineering Geology, **190**, 65-76.

Di Donna, A., Ferrari, A., and Laloui, L. 2016. Experimental investigations of the soil–concrete interface: physical mechanisms, cyclic mobilization, and behaviour at different temperatures. Canadian Geotechnical Journal, **53**(4), 659-672.

Ghahremannejad, B. 2003. Thermo-mechanical behaviour of two reconstituted clays. Ph. D Thesis

Ghionna, V. N., and Mortara, G. 2002. An elastoplastic model for sand–structure interface behaviour. Géotechnique, **52**(1), 41-50.

Graham, J., Tanaka, N., Crilly, T., and Alfaro, M. 2001. Modified Cam-Clay modelling of temperature effects in clays. Canadian geotechnical journal, **38**(3), 608-621.

Hueckel, T., and Pellegrini, R. 1989. Modeling of thermal failure of saturated clays. In International symposium on numerical models in geomechanics. 3 (NUMOG III) (pp. 81-90).

Hueckel, T., and Baldi, G. 1990. Thermoplasticity of saturated clays: experimental constitutive study. Journal of geotechnical engineering, **116**(12), 1778-1796.

Li, C., Kong, G., Liu, H., and Abuel-Naga, H. 2019. Effect of temperature on behaviour of red clay–structure interface. Canadian Geotechnical Journal, **56**(1), 126-134.

Maghsoodi, S., Cuisinier, O. & Masrouri, F. Thermal effects on mechanical behaviour of soil–structure interface. Canadian geotechnical journal **57,** 32–47 (2020).

Pra-ai, S., and Boulon, M. 2017. Soil–structure cyclic direct shear tests: a new interpretation of the direct shear experiment and its application to a series of cyclic tests. Acta Geotechnica, **12**(1), 107-127.

Ravera, E., Sutman, M. & Laloui, L. Cyclic thermomechanical response of fine-grained soil-concrete interface for energy piles applications. Canadian Geotechnical Journal (2020).

Robinet, J. C., Pasquiou, A., Jullien, A., Belanteur, N., and Plas, F. 1997. Expériences de laboratoire sur le comportement thermo-hydro-mécanique de matériaux argileux remaniés gonflants et non gonflants. Revue française de géotechnique, **81**, 53-80.

Yavari, N., Tang, A. M., Pereira, J. M., and Hassen, G. 2016. Effect of temperature on the shear strength of soils and the soil–structure interface. Canadian Geotechnical Journal, **53**(7), 1186-1194.

Yazdani, S., Helwany, S. & Olgun, C. G. Influence of temperature on soil–pile interface shear strength. Geomechanics for Energy and the Environment **18,** 69–78 (2019).