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A load transfer approach for studying the cyclic behavior of thermo-active piles

M.E. Suryatriyastuti [a], H. Mroueh [a,*], S. Burlon [b]

[a] Laboratoire Génie Civil et géo-Environnement (LGCgE) – Polytech'Lille, Université Lille1 Sciences et Technologies, Villeneuve d'Ascq 59655, France
[b] Institut Français des Sciences et Technologies des Transports, de l'Aménagement, et des Réseaux (IFSTTAR), Marne la Vallée 77447, France

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ABSTRACT

Unsatisfactory understanding of thermally induced axial stress and mobilized shaft friction in the thermo-active piles has led to a cautious and conservative design of such piles. Despite the fact that the number of construction works using this type of piles has been rapidly increasing since the last 20 years and none of them witnessed any structural damage, the question that still remains is how to overcome the cyclic thermal effects in such piles to optimize the design method. This paper presents a soil–pile interaction design method of an axially loaded thermo-active pile based on a load transfer approach by introducing a proposed *t–z* cyclic function. The proposed *t–z* function comprises a cyclic hardening/softening mechanism which is able to count the degradation of the soil–pile capacity during two-way cyclic thermal loading in the thermo-active pile. The proposed *t–z* function is then compared to a constitutive law of soil–pile interface behavior under cyclic loading, the Modjoin law. Afterwards, numerical analyses of a thermo-active pile located in cohesionless soil are conducted using the two cyclic laws in order to comprehend the response of such pile under combined mechanical and cyclic thermal loads. The behaviors of the pile resulting from the two laws show a good agreement in rendering the cyclic degradation effects. At last, the results permit us to estimate the change in axial stress and shaft friction induced by temperature variations that should be taken into account in the geotechnical design of the thermo-active pile.

1. Introduction

The thermo-active piles have successfully incorporated the heat exchanger elements to the structural pile foundations. Other than supporting the static weight of structure, the thermo-active piles are used to provide thermal energy to the overlying building by circulating the heat carrier fluid inside the piles [1,2]. In consequence, the thermo-active piles are subjected not only to the mechanical loading of the overlying structure but also to a two-way cyclic thermal loading (i.e. seasonal thermal loading) according to the thermal needs of building. Installation of the thermo-active piles in European countries [3–6] showed that the usage of these piles is advantageous in increasing the energy performance and in minimizing the annual cost [6,7]. But at the same time, this latter presents high risk on the mechanical resistance of both foundations and upper structure [8–10] because the circulating warm fluid during summer produces a pile expansion and the circulating cool fluid during winter produces a pile contraction [11,12]. Besides, no design code that takes into account the thermal interaction on the geotechnical capacity of pile foundations is available yet [13]. For years, contractors have done constructions with thermo-active piles based on empirical considerations or on a conservative design method by increasing the safety factor [13,14]. As a result, a bigger dimension of pile and a higher piling cost are required.

Due to the limited knowledge concerning the impact of thermal operation on the geotechnical performance, the response of thermo-active piles under combined mechanical and cyclic thermal loads becomes a major interest for establishing a more effective geotechnical design criterion. Since the ratio of the pile diameter to the pile length is very small, the temperature variations injected in the pile affects mainly the pile axial response [15]. In situ experiences of the new building at Swiss Federal Institute of Technology in Lausanne [10] and the Lambeth College in London [8] have remarked an important change in mobilized shaft friction and axial load distribution at the soil–structure interface by the change of temperature [16]. These changes are stated to be dependent on the degree of axial fixity at the head and the toe of pile foundation [8,16]. While most reliable method to determine the response of the piles is based on the results obtained from pile load tests, this method can be expensive and time-consuming [17]. Other alternative means to study the axially loaded piles is by conducting

* Corresponding author.
E-mail addresses: msuryatr@polytech-lille.fr (M.E. Suryatriyastuti), hussein.mroueh@polytech-lille.fr (H. Mroueh).

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numerical modeling with finite element analysis or with load transfer analysis (t–z function). The first approach permits to model any constitutive soil behavior with non-linearity and complex soil–structure interaction, but in fact it does not really provide practical solutions for piling problems [18]. The second approach requires to divide the pile into a number of segments supported by discrete springs representing the soil resistance at each shaft element [19,20], where the movement of the pile at any segment is related to the shaft friction at that segment [20].

This paper presents a numerical study of the seasonal temperature induced change in mechanical behavior of pile in the aim to optimize the geotechnical design capacity of the thermo-active piles. The work is based on the concept of soil–structure interaction and thus requires the development of a constitutive law that takes into account the cyclic behavior at the soil–pile interface. Two numerical approaches are proposed: load transfer analysis in one-dimensional model and finite difference analysis in three-dimensional model. In the first part, a development of a nonlinear t–z function at soil–pile interface comprising a cyclic hardening/softening mechanism is presented. This function is then employed to the load transfer method for the design of thermo-active piles in a practical engineering approach. The conceptual background, the workability, and the performance of the proposed function compared to the results from experimental tests are discussed. The second approach used in this work is based on modeling the soil–pile contact using the constitutive interface law Modjoin [21] with finite difference method. This constitutive law had been developed in the laboratory and has recently enhanced to control cyclic degradation phenomena as strain ratcheting, strain accommodation and stress relaxation [22]. The study is distinguished into two extreme head restraint conditions: a free head pile and a fully restrained head pile.

2. Development of t–z function under two-way cyclic loading

The fundamental requirement of load transfer analysis is the appropriate t–z function used to measure the local shaft friction and the relative displacement of soil–pile. A number of t–z curves resulted from in situ static loading tests has been established by Coyle and Reese [23], Coyle and Sulaiman [24], Frank and Zhao [25], and Reese and O'Neill [26]. These t–z curves were originally obtained empirically but may now be obtained more satisfactorily via theoretical relationship with the stiffness of the surrounding soil [27,28].

Randolph has developed a theoretical t–z function under axially cyclic loading and implemented it to RATZ numerical computation program analysis [29,30]. The function consists of a linear elastic part, a nonlinear parabolic shape function describing the strain hardening/softening mechanism, and also a function considering cyclic degradation effects [30,31]. In its recent version, some extensions have been included such as thermal strain in the pile, but it is limited to a single magnitude of the cyclic thermal strains for each analysis. Laboratory of soil mechanics in Swiss Federal Institute of Technology Lausanne has worked on two-way cyclic thermal loading by adding the unloading curve in the t–z curve developed by Frank and Zhao [32]. The curve is implemented into ThermoPile program software, which is designed specifically for analyzing the thermo-active piles behavior [32]. However, the curve is limited to two linear elastoplastic branches and a plateau corresponding to the ultimate stress value without having a kinematic hardening criterion [13,32].

Authors intend to develop a theoretical nonlinear t–z function which is able to describe the cyclic hardening/softening mechanism under two-way cyclic loading. This t–z function is implemented into an algorithm programming language offering a practical design tool for the geotechnical design of thermo-active piles.

2.1. Conceptual background

Generally speaking, the seasonal thermal contraction and dilatation in the thermo-active piles can be equated with a two-way cyclic axial loading. A number of experimental investigations have been carried out to learn the response of piles under cyclic axial loading. Holmquist and Matlock [33] stated that two-way cyclic loading results in a dramatic reduction in the pile load capacity much more than that in the case of one-way cyclic loading. Besides, they pointed out that the reduction in shaft friction has reached up to 75% in the case of extremely large displacement amplitudes. Data collected by Bea et al. [34] showed a remarkable increase in pile head settlement with the number of cycles, causing a reduction in load capacity. On the other hand, Bjerrum [35] and Bea et al. [34] indicated that the more rapid the rate of loading is, the greater the pile capacity becomes. Desai et al. [36] and Fakharian and Evgin [37] concluded that in cohesionless soils, the interface response gets stiffer as the number of cycles increases, while the rate of stiffening decreases.

Poulos found that under two-way axially cyclic loading, the reduction in material volume leads to the reduction in normal stress and consequently to the reduction in shear stress mobilized between the shaft and the soil [18,38]. According to these facts, Poulos concluded that the degradation in shaft resistance depends not only on the reduction in shear stress as a function of absolute cyclic slip displacement, but also on the reduction in normal effective stress due to volumetric strain during cyclic shearing [37,39]. The former component may become more significant in less compressible soils whereas the latter component may dominate in compressible soils.

As a summary, modeling the nonlinear relationship between the shaft friction and the relative displacement at the soil–pile interface under two-way cyclic loading should satisfy the following conditions:

- Reduction in shaft friction with increasing the number of cycles [18,33,34].
- Degradation in shaft resistance with the accumulation of absolute tangential displacement [37,39].
- Reduction in normal stress by the volumetric strain with increasing the number of cycles [39].
- Increase in shaft resistance with a higher loading rate [34,35].
- Increase in pile settlement with increasing the number of cycles [34].
- Hardening and stiffening in interface with increasing the number of cycles [36].
- Decrease in rate of stiffening with increasing the number of cycles [36].

With respect to the hypotheses above, a new formulation of nonlinear t–z function is developed. The proposed t–z function is divided into two stages of loading: the initial relation under monotonic loading and the extension under cyclic loading.

2.2. Proposed t–z function under monotonic loading

2.2.1. Basic principle

Under monotonic loading, the formulation of the proposed t–z function is based on the Frank & Zhao t–z law [25] with respect to the French design standard for the deep foundations design [40]. The shaft friction mobilized at the soil–pile interface q_s related to the tangential displacement u_t is given by: