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Research Paper

Horizontal stress change of energy piles subjected to thermal cycles in sand

C.W.W. Ng, Q.J. Ma *, A. Gunawan

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

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ABSTRACT

Horizontal stress changes of semi-floating energy piles subjected to cyclic thermal loading are investigated through finite element analysis adopting the hypoplastic model. By using the validated finite element model, a parametric study is carried out, considering effects of amplitude of thermal cycles, pile diameter, pile length and relative density of sand. It is revealed that due to volumetric contraction of sand (loose or dense) at the interface under temperature induced cyclic shearing, a reduction of horizontal stress occurs. The degree of reduction in horizontal stress is most affected by the amplitude of thermal cycles and the pile diameter.

1. Introduction

Energy piles have been used to exploit the shallow geothermal energy and gained growing popularity over the past few decades [1–3]. Due to some uncertainties related to the thermo-mechanical performance of energy piles, increasingly more investigations have been carried out. Centrifuge modeling of energy piles in saturated sand [4] and unsaturated silt [5] show that antecedent thermal heating improves the ultimate bearing capacity of energy piles. Full-scale field tests in sand carried out by Wang et al. [6] show that antecedent heating improves the shaft resistance of energy piles. While centrifuge test results from Goode and McCartney [5] show almost no effect of heating on the bearing capacity of energy piles in dry sand. Thermo-elastic numerical analysis carried out by Olgun et al. [7] shows that radial expansion of energy pile due to monotonic heating contributes limited increase in horizontal stress.

For normal operating conditions, however, energy piles are subjected to thermal cycles rather than monotonic heating [1,9,11]. Cumulative settlement behavior was reported for semi-floating energy piles under thermal cycles experimentally [8–10] and analytically by modified load transfer method [11,12]. For end-bearing piles, thermal cycles only have slight effect on the pile head displacement according to test results from Stewart and McCartney [13].

One possible reason for the cumulative settlement of semi-floating energy piles is that when energy piles experience temperature cycles there are repeated pile deformations in both horizontal and vertical directions due to thermal expansion and contraction. This imposes cyclic shearing on soil at the interface, which can result in volumetric contraction of the soil [14]. Therefore, reduction of horizontal stress and shaft resistance is induced according to Boulon and Foray [15]. Consequently, additional pile settlement occurs to further mobilize the base resistance to compensate for the shaft resistance reduction. This change of horizontal stress may be estimated by Eq. (1) proposed by Boulon and Foray [15]

$$\Delta\sigma_h = 4\delta_h\, E_p/D \qquad (1)$$

where δ_h is the change in thickness of the interface soil layer, E_P is the pressuremeter modulus of soil and D is the pile diameter. This equation is derived based on the elastic cavity expansion theory by assuming that the far-field soil behaves elastically. It can be readily deduced that any volume change (elastic or plastic) at the interface soil layer can result in a variation of horizontal stress. When used in practice, an effective pressuremeter modulus should be chosen to account for the stiffness degradation with strain.

The objectives of this study are (1) to validate the above discussed mechanism and (2) to quantify the horizontal stress change of semi-floating energy piles in sand subjected to thermal cycles via finite element analysis.

* Corresponding author.
E-mail addresses: cecwwng@ust.hk (C.W.W. Ng), qmaah@connect.ust.hk (Q.J. Ma), agunawan@connect.ust.hk (A. Gunawan).

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2. Numerical parametric study plan

In this study, bored concrete piles embedded in dry Toyoura sand are simulated as wished-in-place piles. Two series of numerical simulations were performed to investigate effects of the amplitude of thermal cycles (ΔT) and the pile diameter (D). The amplitude of thermal cycles and pile diameter affect the magnitude of pile deformations, and thus volumetric contraction of soil at the interface [14]. For both series, three different relative densities (D_r) are considered to simulate loose, medium-dense and dense sand, respectively.

To investigate effects of pile length, another two series (i.e. Series 3 and 4) of numerical analyses on pile length, ranging from 20 m to 35 m, were carried out. For Series 3, the pile diameter is kept the same at 1.0 m; whereas for Series 4, the pile diameter is also increased from 1.0 m to 1.75 m to maintain the ratio of pile length to pile diameter (L/D) equal to 20.

For all the cases analyzed, compressive axial working load is applied and the overall factor of safety is taken as 2.0 according to the failure criterion proposed by Ng et al. [16]. Full reversal thermal cycles ($\pm\Delta T$) are applied with respect to the reference temperature. Details of the parametric study are listed in Table 1.

3. Numerical modeling methodology

3.1. Constitutive models and model parameters

In order to simulate the above discussed mechanism, primary requirement of the soil constitutive model is to predict the volume change of soil under cyclic shearing. To achieve this purpose, the incrementally nonlinear hypoplastic model for sand developed by Niemunis and Herle [17] is adopted. Niemunis and Herle refined von Wolffersdorff's model [18] by introducing a small elastic range to improve the simulation of sand behavior under cyclic loading. There is no explicitly defined yield surface for the hypoplastic model, and the state-dependent dilatancy of sand behavior can be well simulated. Niemunis and Herle's model needs a total of 13 parameters. All the model parameters and their definitions are summarized in Table 2. Model parameters for Toyoura sand are based on the calibration by Herle et al. [19] and Ng et al. [20].

It should be noted that the adopted hypoplastic model cannot consider thermal effects on soils [21–23]. This study only focuses on the mechanical aspect of the fully-coupled thermo-mechanical soil–structure interaction problem. Heat flow and thermal effects on soil behavior are not considered. It is expected that ignoring thermal effects on soil behavior is likely to underestimate horizontal stress reduction, especially at the first heating–cooling cycle, within which thermally-induced volumetric contraction of sand and normally consolidated clay mainly occurs [21–23].

The concrete energy pile itself is assumed to behave thermo-elastically. Typical parameters for concrete used in this study are in accordance with BS EN 1992-1-2. [24]. Young's modulus, Poisson's ratio, linear coefficient of thermal expansion and density are 3×10^7 kPa, 0.2, 1×10^{-5}/°C and 2500 kg/m^3, respectively.

3.2. Verification of soil constitutive model

To verify Niemunis and Herle's model, a series of cyclic torsional simple shear tests on Toyoura sand by Shahnazari [14] was back-analyzed using the finite element software Abaqus. Implementation of Niemunis and Herle's model in Abaqus is realized by Gudehus et al. [25] through the user subroutine UMAT.

Fig. 1 compares the numerical results to the experimental results of sand volume change under cyclic shearing. The horizontal and vertical axes represent the void ratio e and shear strain γ, respectively. All four tests (a–d) show similar trends between numerical and experimental results. Under cyclic shearing, there is a continuous volumetric contraction of sand, but at a reduced rate. Finally, a stabilized state is reached. Quantitatively, tests b and c show relatively good agreement. For test a (loose sand) the numerical simulation overestimates the stabilized void ratio, while for test d (dense sand) there is a slight underestimation. One possible reason for the discrepancies is that the predefined lower limit compression line in the hypoplastic model, which corresponds to the hypoelastic state, may not be well-represented.

Table 1
A summary of the parametric study.

Series no.	Factor studied	L (m)	D (m)	ΔT (°C)	D_r
1	ΔT	20	1.0	From 5 to 20 at the interval of 2.5	25%, 55%, 85%
2	D	20	From 0.6 to 1.4 at the interval of 0.2	15	25%, 55%, 85%
3	L	From 20 to 35 at the interval of 5	1.0	15	55%
4			L/D = 20		

Table 2
Parameters of the hypoplastic model and their values for Toyoura sand.

	Parameter definition	Parameter symbol	Parameter value
Parameters included in von Wolffersdorff's model	Critical state friction angle	φ'_c	31°
	Extrapolated maximum void ratio at vanishing pressure	e_{i0}	1.10
	Extrapolated minimum void ratio at vanishing pressure	e_{d0}	0.61
	Extrapolated critical state void ratio at vanishing pressure	e_{c0}	0.98
	Parameters controlling the isotropic compression line	h_s	2.6 GPa
		n	0.27
	Parameter affecting the peak strength ratio	α	0.14
	Parameter affecting the incremental stiffness	β	1.1
Additional parameters for Niemunis and Herle's model	Parameter controlling the initial shear stiffness upon 180° reversal of strain path	m_R	11
	Parameter controlling the initial shear stiffness upon 90° reversal of strain path	m_T	6
	Size of the inter-granular strain	R	2×10^{-5}
	Parameter controlling the evolution of inter-granular strain	β_r	0.1
	Parameter controlling the stiffness degradation with strain	χ	1.0