Numerical modelling of energy pile by different constitutive models

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ABSTRACT

Energy pile is an innovative technology which combined foundation pile with heat pumps. Through this integration, foundation pile can then serve as cooling and heating system, in summer and winter, respectively. During energy pile operation, the pile is subjected to heating and cooling cycles. The thermal cycles induce thermal-induced settlement, and predicting this settlement is a major challenge. As the thermal loading of energy pile is cyclic in nature, constitutive model capable of modelling cyclic hysteresis is necessary. In this paper, a model energy pile embedded in saturated sand and subjected to 5 thermal cycles are back-analyzed using hardening soil with small strain stiffness model. To highlight the importance of modelling cyclic hysteresis, two constitutive models which cannot model the cyclic hysteresis, i.e. hardening soil model and Mohr Coulomb model are used to back analyse the same test. Results show that hardening soil with small strain stiffness model can model the test reasonably well, while hardening soil and Mohr coulomb model severely underestimate the thermal-induced settlement.

Keywords: Energy Pile; Numerical Modelling; Pile Settlement

1 INTRODUCTION

Energy piles are the integration of foundation piles with heat pump. This integration enables foundation piles to exchange heat with the ground, thus providing heating or cooling to the building (Brandl, 2006). Exchanging heat with the ground is more efficient than the traditional mean, i.e. exchanging heat with the atmosphere. There are two main reasons for the higher efficiency. The first is the higher thermal conductivity of the ground, the second reason is ground temperature independence from daily and seasonal temperature fluctuations (Preene and Powrie, 2009). In summer, the ground temperature is cooler than air temperature, heat can be expelled into the ground more efficiently than air due to the higher thermal gradient. In winter, the reverse is true. The ground is warmer than air temperature and heat can be extracted from the ground.

Utilization of energy piles have yielded substantial energy savings. For example, in the UK, up to 33% energy savings have been reported (EEBPP, 2000). Despite its environmental benefits, some countries are still reluctant to adopt energy piles (Olgun and McCartney, 2014). This is due to the temperature cycles effect on energy pile serviceability. Thermal cycles cause energy pile to expand and contract. These induce cyclic shearing, compression, as well as extension on the pile surrounding soil (Ng et al., 2016b). Hence, reduction in horizontal stress of energy piles, causing thermal-induced settlement.

These thermal-induced settlements have been observed in many experiments. Among them include tests conducted by Akrouch et al. (2014), Kalantidou et al. (2012), Ng et al. (2014; 2016a), Yavari et al. (2014b; 2016) etc. In the aforementioned experiments, it was found that thermal-induced settlement increases as vertical load and magnitude of temperature change increases; and can occur to energy piles embedded in sand or clay. Several analyses (finite element modelling and load-transfer methods) have shown the same results. Among them include analysis conducted by Ng et al. (2016b), Olgun et al. (2015), Pasten and Santamarina (2014), Suryatriyastuti et al. (2014; 2015).

For non-end bearing energy piles, it is crucial to analyse the long-term behaviour of energy pile so that the pile have sufficient serviceability for the given service load (both axial load and thermal load). In this paper, a centrifuge model test based on Ng et al. (2016a) is back-analyzed using three different constitutive models, i.e. hardening soil with small strain stiffness model (HS-small), hardening soil model (HS) and Mohr Coulomb model. The comparison is conducted to highlight the importance of modelling small-strain stiffness and unloading-reloading hysteresis in modelling the behaviour of energy pile.

The paper briefly summarized the centrifuge model used for back analysis, followed by the numerical modelling methods, model parameters and results.

2 CENTRIFUGE MODELLING

This section summarizes the centrifuge modelling reported by Ng et al. (2016). Only one of the two piles reported is used for the back analysis. In this test, aluminium energy pile with a model diameter of 22 mm and length of 600 mm (645 mm with pile cap) was embedded in saturated medium dense Toyoura sand to 420 mm depth. The test was conducted in 40g (gravitational acceleration) conditions, giving a prototype diameter of 0.88 m and embedment depth equals to 16.8 m. The pile was loaded to 800 kN (prototype scale), equivalent to 50% of ultimate load derived at 10% settlement. Thereafter, 5 thermal cycles with a temperature change of ± 7 ^{0}C were applied to the pile. The pile was then allowed to return to the ambient temperature.

3 NUMERICAL MODELLING

3.1 Numerical model

PLAXIS 2D 2008 was used for the numerical modelling. Figure 1 shows the finite element model. Only half of the pile is modelled under axisymmetric conditions. The side and bottom boundaries are modelled following centrifuge test boundaries. Interface element is added along the pile shaft. Heating and cooling are modelled as thermal boundary along the whole length of the pile shaft and pile base. The average temperature measured along the pile shaft are input as a thermal function to the thermal boundary.

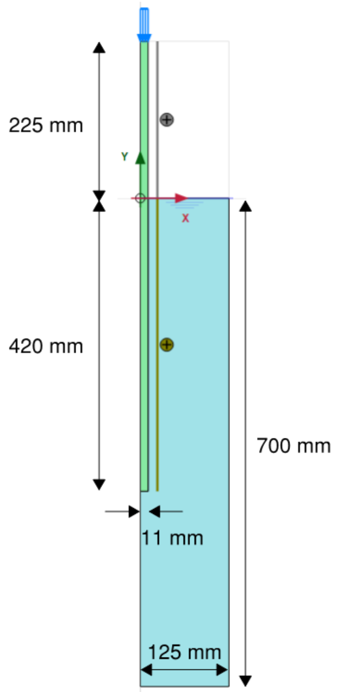


Fig. 1 Dimensions of the numerical model

3.2 Modelling procedure

Gravity loading is used in the initial phase to generate the initial stress in the model. Next, the centrifugal gravity is increased to 40g by increasing the ΣM_{weight} to 40. Working load of 800 kN is then added. Finally, the measured temperature history is input as thermal boundary. During the heating and cooling phase, the calculation type is set as fully coupled flow-deformation.

3.3 Constitutive model and model parameters

The constitutive model used is hardening soil model with small strain stiffness (HSS model). The details of the constitutive model can be viewed in the PLAXIS manual (Brinkgreve et al. 2018). Table 1 summarizes the parameters used for the numerical runs. The parameters have previously been calibrated with a pile load test conducted by the same authors (Ng et al. 2015). Due to the page limit, the calibration is not shown in this paper.

As for the aluminium pile, it is modelled as linear elastic, non-porous material. Table 2 summarizes the parameters used for the aluminium pile. The Young's modulus in table 2 is the equivalent Young's modulus if the hollow pile were a solid pile.

3.4 Comparison with hardening soil model and Mohr-coulomb model

For comparison, the numerical runs were repeated using hardening soil model and Mohr coulomb model. The difference between HS model and HSS model is the absence of two parameters, i.e. $\gamma_{0.7}$ and G_0^{ref}. These two parameters are used to control the small strain behaviour during loading and also unloading. For the Mohr Coulomb model, the Young's modulus is taken as 12 MPa, effective Poisson's ratio as 0.3, as for the effective cohesion, critical friction angle, and dilatancy angle, they are the same as the HS-small model parameters.

Table 1. Model parameters for HS-small model (Gunawan, 2017)

Parameters	Value
Saturated density (γ_{sat})	19.2 kN/m^3
Void ratio (e)	0.71
Effective cohesion (c)	0
Critical friction angle (ϕ'_{cv})	31^0
Angle of dilatancy (ψ)	5^0
Secant stiffness in standard drained triaxial test (E_{50}^{ref})	12 MPa
Tangent stiffness for primary oedometer loading (E_{oed}^{ref})	12 MPa
Unloading/reloading stiffness from drained triaxial test (E_{ur}^{ref})	60 MPa
Power for stress-level dependency of stiffness (m)	0.5
Poisson's ratio for unloading-reloading (ν_{ur})	0.2
Initial shear modulus (G_0^{ref})	200 MPa
Threshold shear strain ($\gamma_{0.7}$) at which $G_s = 0.772\ G_0$	1.35 x 10^{-4}
Specific heat capacity of solid Toyoura sand (c_s)	830 J/kg/K
Thermal conductivity of solid Toyoura sand (λ_s)	4.74 W/m/K
Coefficient of thermal expansion of solid Toyoura sand (α_s)	10 x 10^{-6}

Table 2. Model parameters for Aluminium pile

Parameters	Value
Density (γ)	22.8 kN/m^3
[1] Young's modulus (E)	27.8 GPa
[1] Poisson's ratio	0.33
[1] Strength reduction factor (R_{inter})	0.9

[1] Specific heat capacity of aluminium	875 J/kg/K
[1] Thermal conductivity of aluminium	121 W/m/K
[1] Coefficient of thermal expansion of aluminium	23.2 x 10^{-6}

Reference: [1]ASM (2016)

4 RESULTS

Figure 2 shows the measured results versus the back-analysis results using three different constitutive models. As can be seen from the figure, the HS-small model gives the closest results to the measurement, especially in the first cycle. The final thermal-induced displacement calculated by the HS-small model is 2.7% *D*, where *D* is the pile diameter. The final measurement of pile head displacement after 5 thermal cycles was 4% *D*. One reason for the underestimation is creep. The same aluminium pile loaded to 600 kN (25% less than the pile analyzed) creeped by 0.3% *D* in 5 cycles (Gunawan, 2017). Under higher axial load, the pile would creeped to a higher magnitude. HS-small model cannot consider creep behaviour, hence it shows best agreement in the first cycle, and later the difference between measured and calculated increases. Other differences could be caused by thermally accelerated creep (Akrouch et al. 2014) and thermal contraction of sand (Kosar, 1983; Ng et al., 2016c).

As for Hardening soil model and Mohr Coulomb, the calculated results severely underestimate the thermal-induced settlement of energy pile. In fact, calculation by Mohr Coulomb shows zero thermal-induced settlement at the end of 5 thermal cycles.

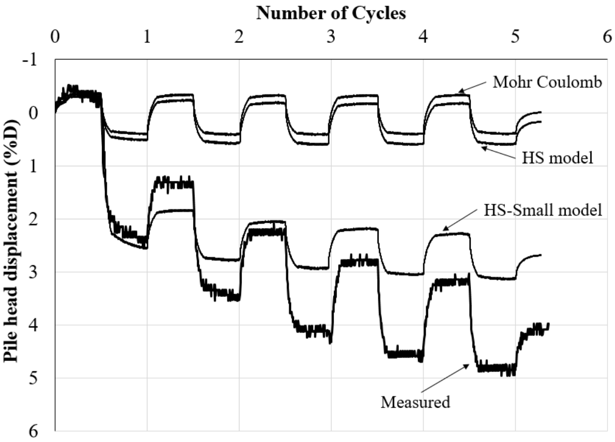
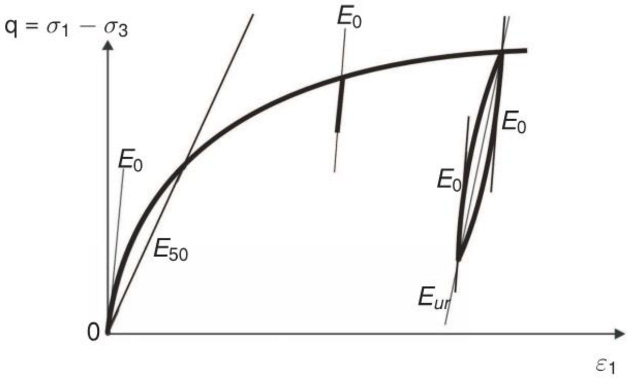


Fig. 2. Comparison of measured and back-analysis using different constitutive models

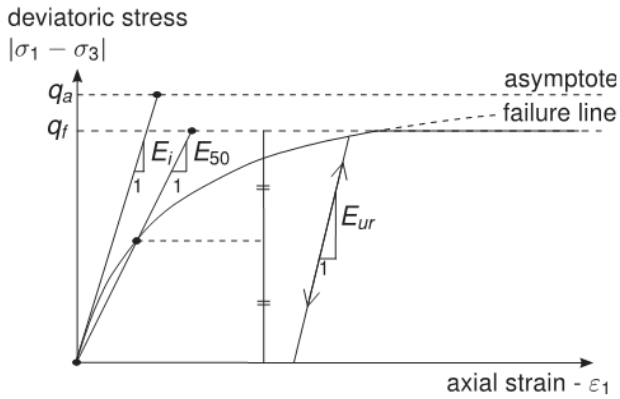
The comparison between HS-Small model and HS model show the importance of modelling small strain stiffness during loading/unloading. By modelling the small strain behaviour, the hysteresis during loading and unloading can be modelled (refer to figure 3a). For HS model, the unloading reloading is modelled as elastic (refer to figure 3b). Hence, the severe underestimation during heating and cooling cycles.

For Mohr Coulomb model, the unloading and reloading path follows the same slope (modulus) as the first loading path. The behaviour is purely elastic as long as the load does not exceed the previous load. Hence, no thermal-induced settlement is observed.

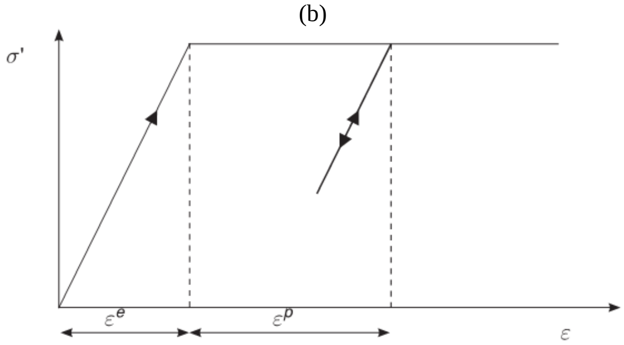
There are previous investigations which use Mohr Coulomb model to investigate energy pile's behaviour and yielded satisfactory results, e.g. Rotta Loria et al. (2015), Yavari et al. (2014a). However, it should be noted that the case analyzed by Rotta Loria et al. was of single heating and single loading case. As for the energy pile field test back-analyzed in Yavari et al.'s case, it was an end-bearing case.



(a)



(b)



(c)

Fig. 3. Stress-strain relationship for: (a) HS-small model; (b) HS model; (c) Mohr Coulomb model (Brinkgreve et al. 2018)

5 CONCLUSIONS

The back-analysis of centrifuge model energy pile test using three different constitutive model highlights the necessity of using constitutive models which are capable of modelling cyclic hysteresis. In fact, for any analysis involving cyclic loading, e.g. wind/wave load, cyclic axial/lateral load etc., constitutive models such as hardening soil model, or Mohr coulomb should not be used. Unfortunately, in practice, simple models tend to be used as it is costly and/or time-consuming to conduct the tests required to obtain the necessary parameters for more sophisticated models. One must be aware of the under-estimation that can be produced by those simple models.

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