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Effect of temperature induced excess porewater pressures on the shaft bearing capacity of geothermal piles

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HIGHLIGHTS

- Geothermal piles in low permeability ($k < 1\mathrm{E}{-11}$ m/s) and low compressibility clays ($K_S > 2\mathrm{E}10$ Pa) can develop excess porewater pressures comparable to shaft friction.
- A shaft friction reduction ratio is presented to account for this.
- The solution presented provides an explanation to the difference between back-calculated and observed shaft frictions for a test pile.

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ABSTRACT

Changes in temperature in clays of low permeability typically induce excess porewater pressures. In the context of geothermal piles this effect has typically been overlooked since most installations have occurred in soils with higher values of permeability. A parametric study is presented that solves the governing differential equations one dimensionally in a pile to study the influence of the various parameters: temperature of the fluid, permeability and soil compressibility. A new shaft resistance reduction ratio has been also defined to illustrate the loss of bearing capacity. The study shows that when the value of permeability is 1E−11 m/s or lower, combined with a soil compressibility in excess of 20,000 MPa, the developed excess porewater pressures can potentially reduce the effective stress locally to very low values. The solution applied to the case of the Lambeth College, London, also provides a plausible explanation to the observed loss of shaft friction of the tested pile.

1. Introduction

Soils with low permeability can experience substantial increases in their porewater pressures as a consequence of temperature rises (e.g. Refs. 1–4).

Geothermal piles are used to exchange heat from the ground for heating and cooling of superstructures.[5] In their cooling mode, the temperature of the circulated fluid is higher than the soil's temperature; hence, increasing the temperature of the latter. Under normal operating conditions the fluid can be up to 30 °C, although greater temperatures have been tested (e.g. Refs. 5, 6). In low permeability soils, these temperature increases have the potential to increase the porewater pressures and reduce the available effective stress. If this reduction is in the same order as the mobilised shaft friction, their effect on the shaft resistance can be significant.

In order to study the full thermo-hydro-mechanical interaction between pile and soil, Laloui et al.[7] presented the complete formulation of the problem and a solution compared to a field test. The excess porewater pressures are included implicitly within the formulation but since the values of permeability reported in their case study were in the order to 10^{-6} m/s, no significant excess porewater pressures were observed and remained constant. In turn, this had little effect on the available shaft friction. However, in the presence of lower permeability soils, these excess porewater pressures can reach values in the order of 1 MPa for temperature increments of 30 °C,[3] which in most practical cases of bearing piles would exceed the effective stress at the interface. Bourne-Webb et al.[6] presented another pile test with temperature cycling where they reported a difference of 15 kPa between the back-analysed –

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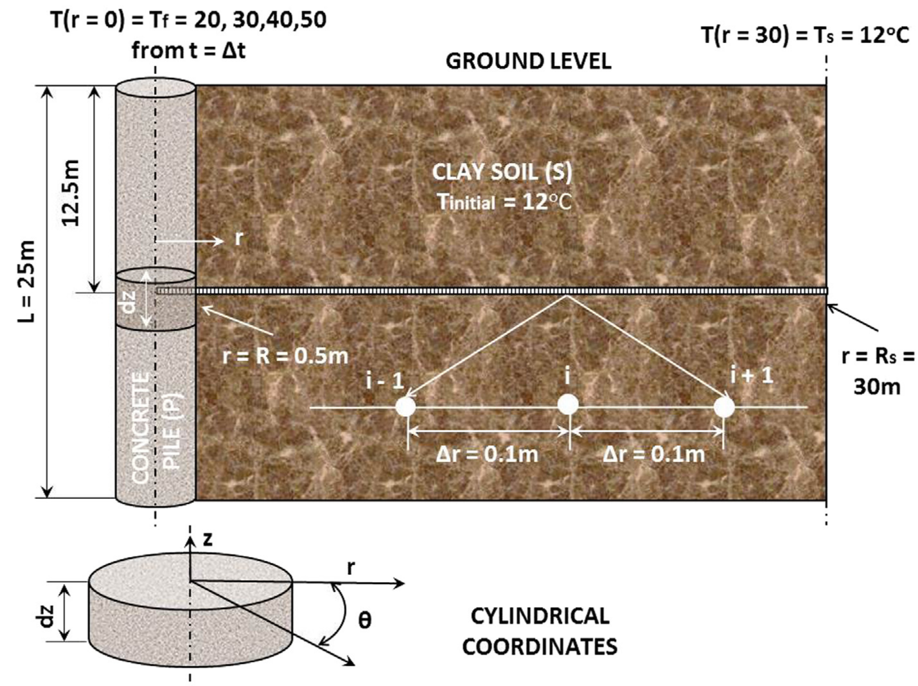

Fig. 1. Problem definition.

based on a mechanical test – shaft friction and the measured shaft friction as will be shown later in the paper.

Based on this evidence, this paper presents a finite difference solution to the fully coupled formulation to study the development of excess porewater pressures in geothermal piles and its impact on the shaft friction at the pile–soil interface. The emphasis will be on presenting comparisons in terms of orders of magnitude of excess porewater pressures and not attempting to specify accurately all properties as this will change from case to case. These comparisons do however, highlight an important issue that has been so far overlooked. The solution also provides a plausible explanation to the differences observed during the Lambeth College test presented in Ref. 6.

2. Problem definition, governing equations and assumptions

Fig. 1 shows the problem's geometry. A single pile diameter equal to 1 m and pile length of 25 m as used by Bourne-Webb et al.[6] were used. This length is enough to guarantee that seasonal effects are less important at mid-depth of the pile[8] where the comparison between methods is carried out.

The problem presents geometrical axisymmetry about the pile's axis so a cylindrical coordinate system (r, θ, z) was chosen as shown in Fig. 1. Additionally, Loveridge & Powrie[9,10] showed that the temperature difference at the pile surface for different positions within a pile diameter is lower than 2 °C: therefore, the azimuthal coordinate, θ, can be eliminated. Likewise, it is assumed that the temperature of the pile along its length is constant; this has been verified in site tests by multiple authors—e.g. Refs. 6, 7 for piles or Lee & Lam[11] for boreholes. This, combined with an assumption of fully hydrostatic initial porewater profile, allows eliminating the z coordinate as well. The problem then becomes one dimensional, defined in the radial direction, r. It must be noted that this assumption is more representative of points distant from the ground surface where the temperature of the soils is subject to variations from above-ground effects. Hence, the comparisons between calculation methods – explained later – were done at mid-depth of the pile as indicated in Fig. 1.

The thermo-hydro-mechanical formulation that defines the problem was presented generally by Olivella et al.,[12] and its application to piles by others like Laloui et al.[7] Both references present the full equations derivation and therefore, this paper only presents the final equations. For ease of reference, the reader is directed to Pinyol & Alonso[4] as the same nomenclature has been used here.

The heat equation for a constant thermal conductivity is

$$\frac{\partial T}{\partial t} = \alpha \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \alpha\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right) \quad (1)$$

where the convection effects have been ignored as demonstrated by Laloui et al.[7] for values of permeability much higher than those covered here: hence, this assumption is even more applicable to our case.

The combination of soil and water mass balance formulations yields the final governing second order parabolic differential equation that applies only to the soil mass[4]

$$-\left[(1-n)\,\beta_s + \beta_w n\right]\frac{\partial T_s}{\partial t} + \left(n\alpha_w + \frac{1}{K_s}\right)\frac{\partial u}{\partial t} - \frac{k}{\gamma_w}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) = 0 \quad (2)$$

which has as unknowns the soil temperature, T_s, and the excess porewater pressures, u.

The main assumptions to derive the above equation are:

- The soil grains are incompressible against stress but not temperature changes.
- All the input variables – porosity, thermal conductivity, permeability, soil and water linear coefficients of thermal expansion, and soil and water compressibility – are independent of time, temperature and stress.
- The water table does not change throughout the test and therefore, in combination with small seepage forces due to low permeability, all changes to porewater pressures are due to the induced excess porewater pressures caused by thermal and mechanical strains.