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A numerical model for penetration and heat conduction of thermal cone penetration test with an optimization method for interpretation

Modèle numérique pour le test de pénétration et de conduction thermique d'un cône thermique avec une méthode d'optimisation pour l'interprétation

Pin-Qiang Mo, Yu-Chen Hu & Zhi-Wen Ren
State Key Laboratory for GeoMechanics and Deep Underground Engineering, School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, 221116, China

Feng Gao
School of Civil & Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia

ABSTRACT: Geothermal energy pile can provide majority of required heating/cooling energy, save energy costs, and reduce fossil fuel demand and carbon footprint, and the thermal cone penetration test (T-CPT) has been proposed and applied to obtain thermal properties using the recorded temperature changes with time. After conventional penetration, the probe temperature tends to increase caused by the friction between the penetrometer and soil layers, whereas thermal resistor could also be installed to provide a known heat flux to the penetrometer during the heating stage. Temperature dissipation occurs during the following cooling stage, while the transient heat conduction with complex boundary condition dominates the heat transfer from probe to soil. The response of temperature changes would therefore be adopted to estimate thermal properties of soil, including in-situ temperature, thermal conductivity, and specific heat capacity. This paper proposes a numerical model for penetration and heat conduction, by using cylindrical cavity expansion method and a finite difference model for axisymmetric probe-soil heat conduction. The penetration induced stresses and strains in the surrounding soil are calculated to evaluate the changes of density, specific volume, and thus thermal properties. After analyzing the existing interpretation methods, an optimization method using algorithm of Particle Swarm Optimization (PSO) is then suggested to obtain the best-fit thermal properties. The proposed method can then be applied for the interpretation of thermal and mechanical properties from T-CPT data. The obtained profiles with thermal properties are potentially used to evaluate the feasibility of geothermal energy piles, and thus contribute to the optimization of state-of-the-art design methods.

RÉSUMÉ : La pile d'énergie géothermique peut fournir la majorité de l'énergie de chauffage / refroidissement requise, économiser les coûts énergétiques et réduire la demande de combustibles fossiles et l'empreinte carbone, et le test de pénétration du cône thermique (T-CPT) a été proposé et appliqué pour obtenir des propriétés thermiques en utilisant les changements de température enregistrés avec le temps. Après la pénétration conventionnelle, la température de la sonde a tendance à augmenter en raison du frottement entre le pénétromètre et les couches du sol, tandis que la résistance thermique pourrait également être installée pour fournir un flux de chaleur connu au pénétromètre pendant l'étape de chauffage. La dissipation de la température se produit au cours de l'étape de refroidissement suivante, tandis que la conduction de chaleur transitoire avec des conditions aux limites complexes domine le transfert de chaleur de la sonde au sol. La réponse des changements de température serait donc adoptée pour estimer les propriétés thermiques du sol, y compris la température in situ, la conductivité thermique et la capacité thermique spécifique. Cet article propose un modèle numérique pour la pénétration et la conduction thermique, en utilisant la méthode d'expansion cylindrique de cavité et un modèle de différence finie pour la conduction thermique axeymétrique sonde-sol. Les contraintes et les déformations induites par la pénétration dans le sol environnant sont calculées pour évaluer les changements de densité, de volume spécifique et donc de propriétés thermiques. Après avoir analysé les méthodes d'interprétation existantes, une méthode d'optimisation utilisant l'algorithme d'optimisation de l'essaim de particules (PSO) est ensuite suggérée pour obtenir les propriétés thermiques les mieux ajustées. La méthode proposée peut ensuite être appliquée pour l'interprétation des propriétés thermiques et mécaniques à partir des données T-CPT. Les profils obtenus avec des propriétés thermiques sont potentiellement utilisés pour évaluer la faisabilité des pieux d'énergie géothermique, et contribuent ainsi à l'optimisation des méthodes de conception de pointe.

KEYWORDS: Thermal cone penetration test; heat conduction; cavity expansion method; interpretation, optimization.

1 INTRODUCTION

China has announced that it would aim to achieve peak CO_2 emissions before 2030 and carbon neutrality before 2060. Peaking CO_2 emissions and reaching carbon neutrality require extensive and profound systematic changes, especially to the green low-carbon energy development. Geothermal energy is reckoned to be green and sustainable for both heating and cooling (Capareda, 2019; Altun and Kilic, 2020). Regarding to the shallow geothermal energy, energy pile is a newly developed type of foundation that can provide majority of required energy, save energy costs, and reduce fossil fuel demand and carbon footprint (Faizal et al., 2016; Huang et al., 2019). For the efficient and effective use of shallow geothermal energy, the in-situ thermal properties of soil or rock layers are therefore the most important information for the design and construction of geothermal applications. Compared to the traditional thermal response tests with limitations on time consuming and averaged response, more convenient in-situ testing methods have been proposed to obtain local thermal responses for the interpretation of thermal properties (Akrouch et al., 2016; Vardon et al., 2019). In this study, a new thermal cone penetrometer is proposed, and its numerical model is developed with considerations of penetration induced disturbances and heating/cooling tests after certain pauses of penetration. The stress/strain distributions around the probe are obtained through the cylindrical cavity expansion solutions, and the changes of soil density and specific volume are evaluated to assess the variations of thermal properties within the plastic region induced by penetration. A PSO-based interpretation method is then developed for the further improvement on the back-analyses of thermal and mechanical properties based on the measurements of thermal cone penetration testing.

2 THERMAL CONE PENETRATION TEST

2. *Probe and testing procedure*

Mo et al. (2021) reported a thermal cone penetration test (T-CPT) which equipped the conventional CPTu tool with heating elements and three temperature sensors for capturing thermal responses during heating and cooling, and the schematic of this probe with probe radius $r_{probe} = 17.8\text{mm}$ is shown in Figure 1. The traditional CPTu part measures the con tip resistance (q_c), sleeve friction (f_s), and excess pore water pressure at probe shoulder (u_2) during penetration; whereas the thermal part applied the heating flow with records of temperatures at various positions. Typically, the thermal test is conducted during the ease of penetration at a certain depth, and the thermal responses are captured to back-calculate the in-situ thermal properties.

The testing procedure of the T-CPT includes the following steps: (1) probe pushing stage with measurements of q_c, f_s, u_2 against penetration depth z; (2) probe pausing stage to conduct heating and cooling tests at a given depth z_i; (3) repeat steps 1-2 to the next depth. Note that the thermal tests normally have two different modes: (1) cooling test without using the heating elements, and the probe surface temperature increases due to the probe-soil interface friction during probe pushing; (2) heating-cooling test. According to Mo et al. (2021), to account for this temperature increase, a pausing stage would be required to allow for temperature dissipation before the heating and cooling tests. Since full dissipation might require an impractically long period of time, a pausing time before heating is suggested to be less than 5 minutes, and the temperature responses can be adopted to assist the interpretation according to Vardon et al. (2019). Alternatively, the penetration can be paused at a certain distance ahead of the target depth for temperature dissipation, and the subsequent push brings limited temperature disturbance to the target soil layer. Temperature measurements at various locations during the probe pushing and pause stages are available for mutual support of the thermal interpretation.

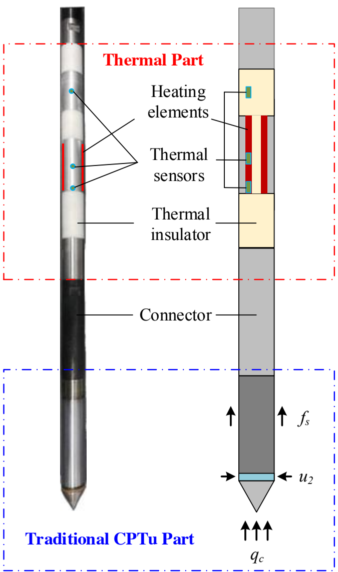

Figure 1. Schematic of T-CPT.

2.2 *Interpretation and penetration effects*

Interpretation of CPTu data has been well developed for the evaluation of soil type and properties of soil layers (e.g. void ratio, relative density, overconsolidation ratio, strength parameters, stiffness, compressibility, consolidation coefficient, permeability, coefficients of lateral earth pressure, dilatancy, etc.), according to Mayne (2007) and Robertson & Caval (2010). Regarding to the T-CPT, the interpretation of thermal testing data is vital to provide quick estimations of thermal properties, including thermal conductivity (k) and specific heat capacity (c). However, the available interpretation is mainly based on either empirical approaches or oversimplified analytical solutions.

ASTM (2014) proposed a standard test method for determination of thermal conductivity of soil by thermal needle probe test. However, the back-calculation used a theory that is only suitable for an infinitely thin line source, and calibration factors are not widely applicable for T-CPT penetrometers. Akrouch et al. (2016) adopted the strategy with analogues between T-CPT and pore water dissipation test or consolidation test. The empirical equations for back-calculation of soil hydraulic conductivity were imitated for estimation of thermal properties, according to the equivalency between thermal and hydraulic flow problems. Calibration using numerical simulation was conducted to obtain unknown parameters through hyperbola curve fitting. This empirical method is lack of theoretical evidences, and volumetric heat capacity of soil must be provided for estimations.

Similarly, Vardon et al. (2019) suggested to perform cooling tests without installing heating elements, attributing to the temperature rise generated by the probe-soil interface friction. However, concerns need to be taken for accurate estimation of inputted heat amount and its variation in different soils at various depths. Heating elements with known thermal power are therefore suggested to rise the probe temperature steadily and sufficiently. Both heating and cooling responses can be used for mutual interpretation. Although interpretation based on both direct method from data and graphical method was reported by Vardon et al. (2019), its feasibility to heating-cooling tests is thus questionable, and temperature sensor embedded at the cone tip needs to be corrected for spherical heat conduction. Moreover, the initial state induced by the preceding penetration is too complex to be considered in the interpretation method, and the soil densification during probe pushing may disturb the in-situ profile of thermal properties.

A centrifuge test of CPT by Mo et al. (2015) showed that the horizontal displacement field around the probe shoulder is almost uniform, as shown in Figure 2, which is analogous to the cylindrical cavity expansion. The penetration induced soil densification results in the changes of thermal properties for soil adjacent to the probe, which would have significant effects on the subsequent heat conduction during the heating-cooling of T-CPT, as depicted in Figure 2. Therefore, this study attempts to propose a numerical model with consideration of both penetration and heat conduction, as will be described in the next section.

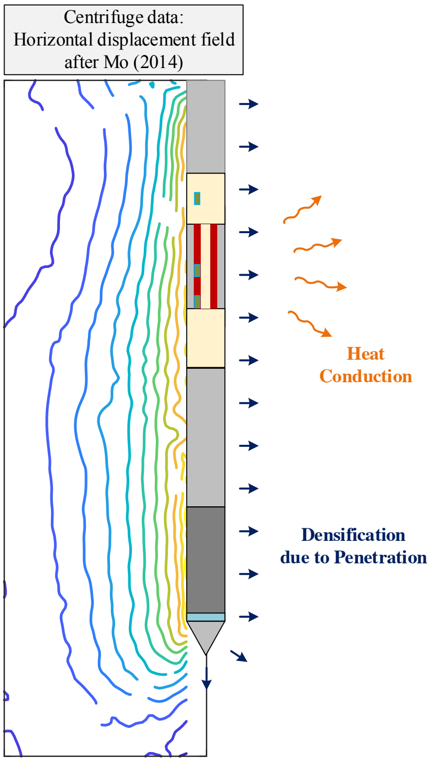

Figure 2. Penetration induced displacement field and the subsequent heat conduction of T-CPT.

3 NUMERICAL MODEL FOR PENETRATION AND HEAT CONDUCTION

3.1 *Cylindrical cavity expansion*

During penetration, soil is pushed away to accommodate the probe, and the soil around the probe shaft is analogue to cylindrical cavity expansion. Mo & Yu (2018) proposed an analytical solution for drained expansion of both spherical and cylindrical cavities using CASM (Yu, 1998). CASM is a critical-state based soil model for capturing overall behaviour of clay and sand, and the large-strain solution has been used to analyze the relationship between cone tip resistance and soil state parameter (Mo & Yu, 2018, Mo et al., 2020). In this study, soil around the probe shaft is reckoned to be affected by the penetration, and the induced changes to effective stress condition and void ratio can severely affect the thermal responses during the heating and cooling stages.

3.2 *1D numerical model of heating and cooling*

The one-dimensional transient heat conduction model for heating and cooling in the probe-soil system has been elaborated in Mo et al. (2021). The explicit solution was adopted to satisfy the first law of thermodynamics in a cylindrical axisymmetric coordinate, which was then verified against analytical solutions and numerical simulation. Note that when the length of the heating element is limited, and the calculation of heating conduction from the 1D numerical model should be modified by introducing correction factors.

3.3 *Model parameters*

3.3.1 *Mechanical properties of soil in CASM*

The mechanical properties of soil are selected to model Leighton Buzzard sand based on Hu (2015), and the model parameters are: $\Gamma = 1.8$; $\lambda = 0.025$; $\kappa = 0.005$; $\mu = 0.16$; $n = 2.0$; $r^* = 33$; $\phi_{tx} = 32.0°$; $M = 1.1756$ for cylindrical scenario. The initial state conditions are set based on the soil with relative density of 90% at 10m depth, with initial stress condition $p_0' = 104.3$kPa; initial specific volume $\nu_0 = 1.653$; initial state parameter $\xi_0 = -0.0307$; initial overconsolidation ratio $R_0 = 153$.

3.3.2 *Thermal properties of saturated soil*

By adopting the assumption of parallel isotherms, the effective thermal conductivity of a two-phase medium is evaluated using Eq. 1, according to Gori & Corasaniti (2004), for saturated soil in this study.

$$\frac{1}{k} = \frac{\beta-1}{k_w \cdot \beta} + \frac{\beta}{k_w \cdot (\beta^2-1)+k_s} \qquad (1)$$

where k is the effective thermal conductivity of the soil analogue; k_w and k_s are the thermal conductivities of the liquid and solid phases, respectively; β is a parameter related to the soil porosity n:

$$\beta = \sqrt[3]{\frac{1}{1-n}} \qquad (2)$$

The heat capacity of soil is estimated with the following Eq. 3:

$$\rho \cdot c = (\rho_w \cdot c_w) \cdot n + (\rho_s \cdot c_s) \cdot (1-n) \qquad (3)$$

where c is the effective specific heat capacity of the soil with density ρ; ρ_w and ρ_s are the densities of the liquid and solid phases, respectively; c_w and c_s are the specific heat capacities of the liquid and solid phases, respectively. In this study, the initial thermal properties of soil are: $k_0 = 1.741$W/m/K, $c_0 = 1479$J/kg/K.

4 RESULTS

4.1 *Results of cylindrical cavity expansion*

The stress-strain distributions after cylindrical cavity expansion from grain size to probe size are shown in Figure 3, representing the soil states after probe penetration. The plastic zone is about 15 times of probe size, and the radial stress at the vicinity of probe is close to $15p_0'$. Both radial and tangential strains increase significantly within the region of $5r_{probe}$, which validate the necessity of large-strain assumptions in the plastic region. Typically, the stresses at the probe surface are used to analyze the cone tip resistance and shaft resistance, for the interpretation of CPT data.

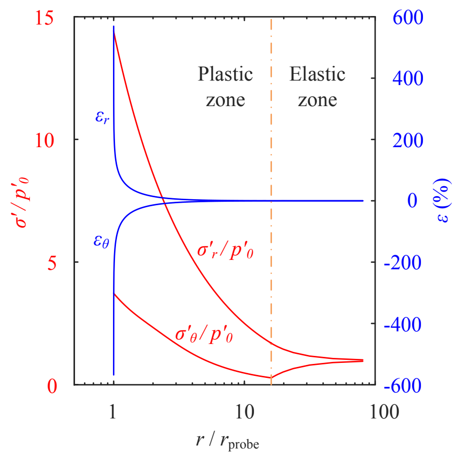

Figure 3. Stress and strain distributions after probe penetration.

Due to the penetration induced densification to surrounding soil, the distributions of specific volume v and density ρ are described in Figure 4(b), showing the disturbance within the plastic region. Accordingly, the distributions of thermal properties (specific heat capacity c, thermal conductivity k and thermal diffusivity $\alpha = k/\rho/c$) after penetration are presented in Figure 4(b). The thermal conductivity increases from 1.741W/m/K to 1.765W/m/K, whereas the specific heat capacity decreases from 1479J/kg/K to 1460J/kg/K. These variations of thermal properties could affect the thermal conduction in the probe-soil system, and in turn cause errors in the interpretation of thermal properties. Therefore, the results of cylindrical cavity expansion are important for the assessment of penetration induced disturbance.

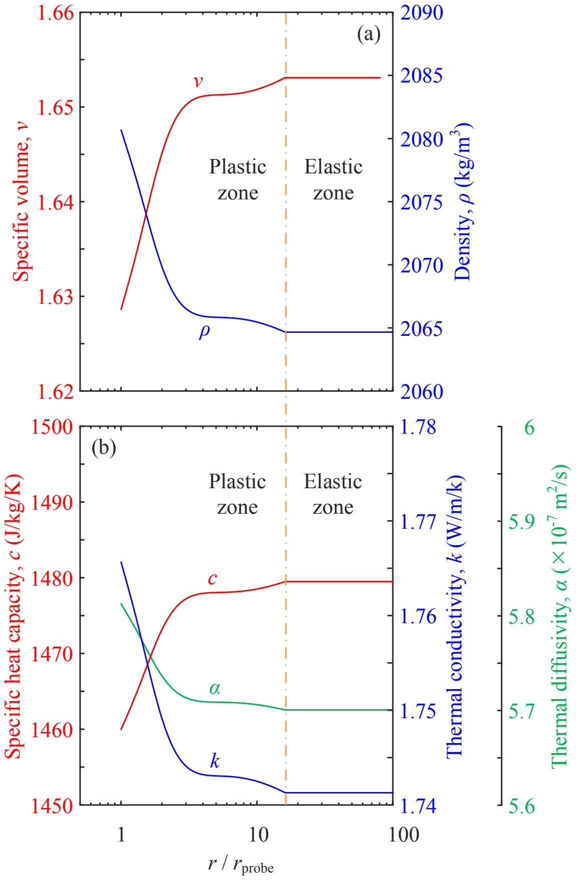

Figure 4. Distributions of (a) specific volume and density; (b) specific heat capacity, thermal conductivity and thermal diffusivity of soil around penetrometer.

4.2 *Results of heating and cooling*

The initial soil temperature is set as 20℃, and the effect of friction induced temperature rise is neglected in this study. The heating stage after pause of penetration lasts for 10mins, with a constant heat flux q_0=100W/m, followed by a 100mins of cooling stage. The temperature at the probe surface during heating and cooling stages is depicted in Figure 5(a), noting that the temperature rises to 25.5℃ after 10mins' of heating. The labeled points after peak indicate the temperatures at 20, 40, 60, 80, 100mins, respectively. Correspondingly, the temperature distributions at these moments are described in Figure 5(b). The heat conducts and dissipates from the probe surface, while the influence zone increases with cooling time. Typically, the measured temperature response is adopted to back-calculate the thermal properties, which will be discussed in the following sections.

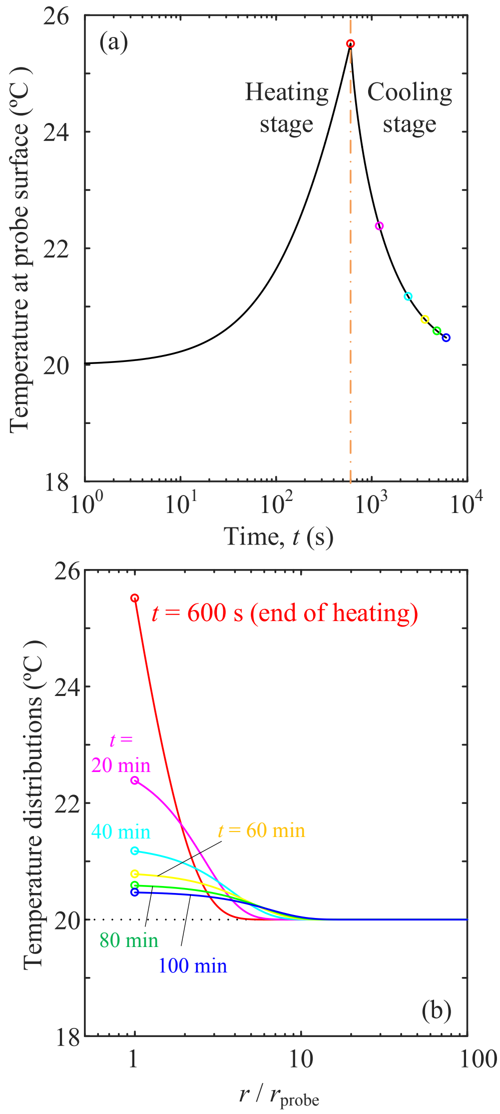

Figure 5. Temperature responses during heating and cooling stages: (a) temperature at the probe surface; (b) temperature distributions in the soil.

4.3 *Interpretation of T-CPT data*

As reported by Mo et al. (2021), ASTM (2014) proposed a standard test method for the determination of soil thermal conductivity by a thermal needle probe test, which is usually adopted as a benchmark for the analysis of thermal response tests. This method however has some limitations, since it cannot consider the influences of heat capacity, probe size, and penetration disturbance.

Taking the thermal response from Figure 5(a) as the measured data, interpretation using the ASTM method is depicted in Figure 6 for both heating and cooling stages. The ASTM method suggests to plot the heating data in the $\Delta T - \ln t$ space and the cooling data in the $\Delta T - \ln\left[t/\left(t - t_{heating}\right)\right]$ space. The later periods of heating and cooling tend to reach asymptotes, and their slopes are related theoretically to the magnitude of thermal conductivity. The results in Figure 6 show that the linear fitting gives good performance, while the heating stage leads to $k_h =$ 2.563W/m/K and the cooling stage leads to $k_c = 1.883$W/m/K. Compared to the soil thermal parameter $k_0 = 1.741$W/m/K, the back-calculation overestimates the thermal conductivity, especially from the heating data. Longer heating or cooling time could help to improve the estimations, whereas the efficiency is then limited and the influence of adjacent soil layers could be non-negligible. As to the concept of T-CPT with fast measurements of mechanical and thermal properties of soil layers, the interpretation requires to be developed using more sophisticated methods, as attempted in the following section.

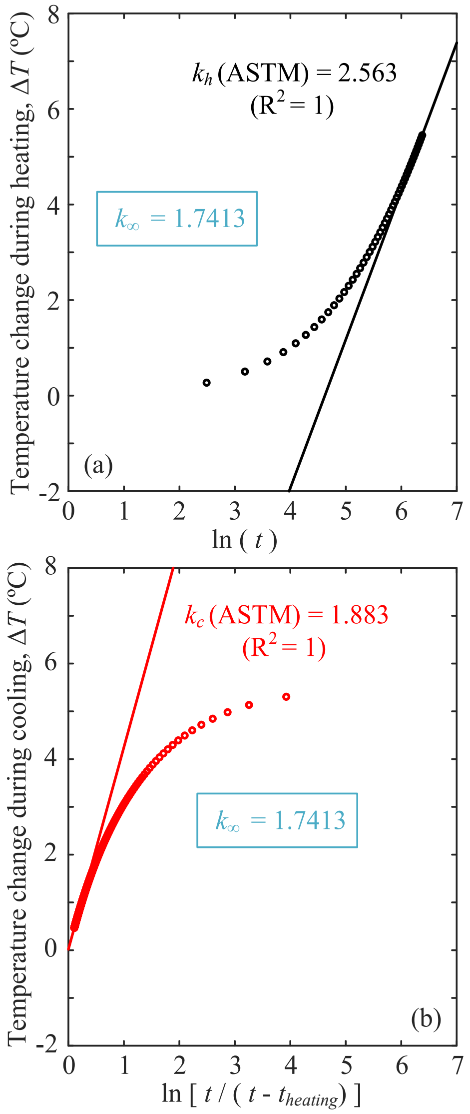

Figure 6. Interpretation using the ASTM method: (a) heating stage; (b) cooling stage.

5 PSO-BASED OPTIMIZATION

Mo et al. (2021) has proposed an optimization method for the interpretation of thermal properties of soil, which is based on the technique of particle swarm optimization (PSO) and is also adopted in this study.

The general PSO procedure is briefly described with the schematic flowchart in Figure 7(a). Given a swarm size, n_p particles with initially random positions and velocities are created and assigned within the working space. For each particle, the error function $Error(\boldsymbol{x})$ is formulated to evaluate the error between the target data and the predicted result RMSE, and $\boldsymbol{x}$ is a vector of parameters for optimization, which ranges between the lower and upper bounds (i.e. $\boldsymbol{x}^{LW}$ and $\boldsymbol{x}^{UP}$). To search for the optimal solution, the i^{th} particle with its position $\boldsymbol{x}_i^t$ moves at a specified particle velocity $\boldsymbol{v}_i^t$ (i.e. step size) with combined influences of personal best position $\boldsymbol{pBest}_i^t$, global best position $\boldsymbol{gBest}^t$ and some random perturbations.

Taking the numerical results as the target data, an example of PSO-based interpretation of T-CPT data for both thermal conductivity and heat capacity is shown in Figure 7(b). In this case study, about 1000 datapoints from the target data with a timestep of 1s are taken to compare with the predicted temperature values at the same time distribution. The swarm size and maximum iterations are set as $n_p = 10$ and $t_{max} = 50$, respectively. The decrease in RMSE against iterations shown in Figure 7(b) indicates that 30 iterations with 10 initial particles perform well for the interpretation.

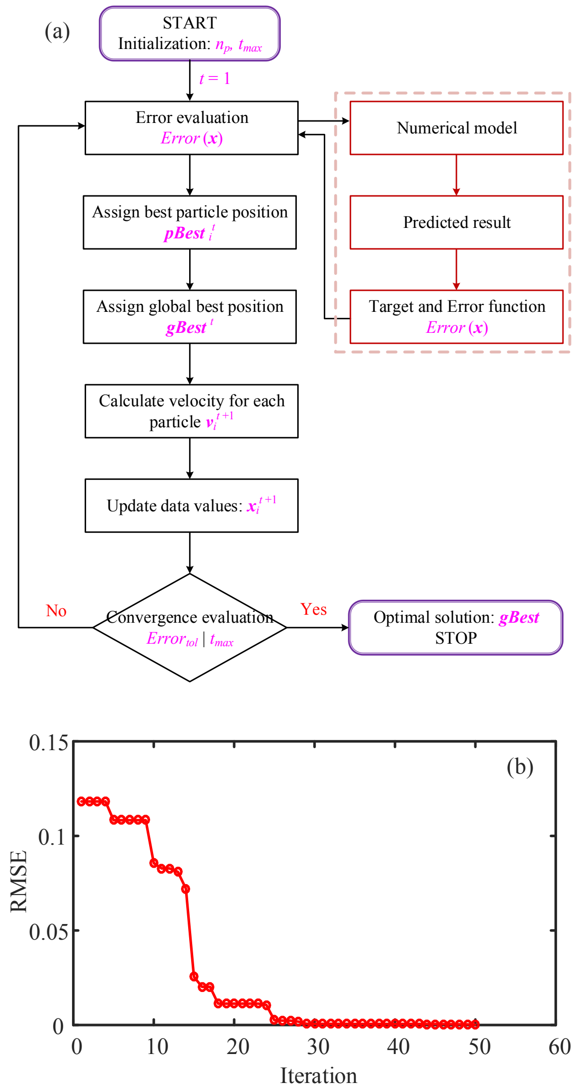

Figure 7. PSO-based interpretation: (a) flowchart of the PSO algorithm; (b) performance of PSO method with RMSE against iterations; after Mo et al. (2021).

6 CONCLUSIONS

This paper proposes a numerical model for penetration and heat conduction of a thermal cone penetration test, considering the penetration disturbance and heat conduction in the probe-soil system. Cylindrical cavity expansion in CASM is adopted to calculate the penetration induced stresses and strains around the probe, and the changes to the specific volume and density affect the distributions of thermal properties of surrounding soil. The disturbed soil is then considered as the initial states for the subsequent heat conduction during heating and cooling stages.

A cylindrical axisymmetric probe-soil heat conduction, using finite difference method with explicit expressions, which is validated against analytical solutions and numerical simulations. The temperature at the probe surface and the temperature distributions in the soil are obtained at various periods. The thermal response is then used to back-calculate the thermal conductivity following the ASTM method, showing the overestimation of thermal conductivity with limited heating and cooling time.

An optimization method using algorithm of Particle Swarm Optimization (PSO) is then suggested to obtain the best-fit thermal properties, by analyzing the best value of root mean square error between the measured and predicted data. The proposed method shows acceptable performance with limited calculation resource, and it is applicable for further developments with interpretations of thermal and mechanical properties from T-CPT data with or without heating stage. The obtained profiles with soil properties are potentially used to evaluate the feasibility of geothermal energy piles, and contribute to the optimization of state-of-the-art design methods.

7 ACKNOWLEDGEMENTS

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