Visualization of heat transfer to characterize energy foundations

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ABSTRACT
Limited information exists about the thermo-dynamic interactions of geothermal structures and soil owing to practical constraints of placing measurement sensors in proximity to foundations. An alternative experimental method is explored using transparent soil to enable internal visualisation of heat flow in soil. Advocating the loss of optical clarity as a beneficial attribute of transparent soil, this paper explores the hypothesis that temperature change will alter its refractive index and therefore progressively reduce its transparency becoming more opaque. The development of the experimental methodology is discussed and a relationship between pixel intensity and soil temperature is defined and verified. This relationship is applied to an energy pile example to demonstrate heat flow in soil. The heating zone of influence is observed to extend to a radial distance of 1.5 pile diameters and is differentiated by a visual thermal gradient propagating from the pile.

RÉSUMÉ
Peu d'information existe sur les interactions thermodynamiques entre les structures géothermiques et le sol à cause des contraintes pratiques qu'implique le placement de capteurs de mesure près des fondations. Une méthode expérimentale de remplacement est explorée à l'aide de sol transparent pour permettre la visualisation interne du flux de chaleur dans le sol. Prônant la perte de clarté optique comme un attribut bénéfique du sol transparent, cet article explore l'hypothèse que le changement de température modifie son indice de réfraction et donc réduit progressivement sa transparence le rendant de plus en plus opaque. Le développement de la méthode expérimentale est discuté et une relation entre l'intensité des pixels et la température du sol est définie et vérifiée. Cette relation est appliquée à un exemple de pieu énergétique afin de démontrer un flux de chaleur dans le sol. Il a été observé que la zone d'influence du réchauffement s'étend à une distance radiale de 1,5 fois le diamètre du pieu et se distingue par un gradient thermique visible se propageant à partir du pieu.

1 INTRODUCTION

Managing natural resources is becoming one of the crucial issues of the 21st century and is closely linked to the need to reduce our carbon footprint and become more energy sustainable. Geotechnical energy structures/foundations are believed to offer potential to make a positive contribution to this vision by serving as energy exchange systems to regulate building environmental conditions. In winter the ground temperature is higher than the air and it therefore provides a potential source of heat energy; alternatively, in summer the ambient air temperature is higher and the ground can be used as a heat sink to cool the building; thus reducing the reliance on conventional heating and cooling systems (Figure 1).

The concept of ground energy exchange systems have been proposed and implemented for decades with Brandl (2006) reporting on the first installation of thermal piles in the 1980's. Despite this period since their initial deployment, design methods for their thermal or geotechnical aspects are not yet well established (Loveridge and Powrie 2012). Many researchers have conducted element tests to study the behaviour of soils subjected to temperature changes such as Campanella and Mitchell (1968), Plum and Esrig (1969), Habibagahi (1977) and Boudali et al. (1994), all reporting changes in stress, volume and strength in over-consolidated and normally consolidated soils for both heating and cooling. These changes could have considerable implications on the thermo-mechanical response of foundations (i.e. energy piles) deployed as energy structures; such that, under working stress, deterioration of stability and serviceability could manifest leading to uncertainty in long term performance.

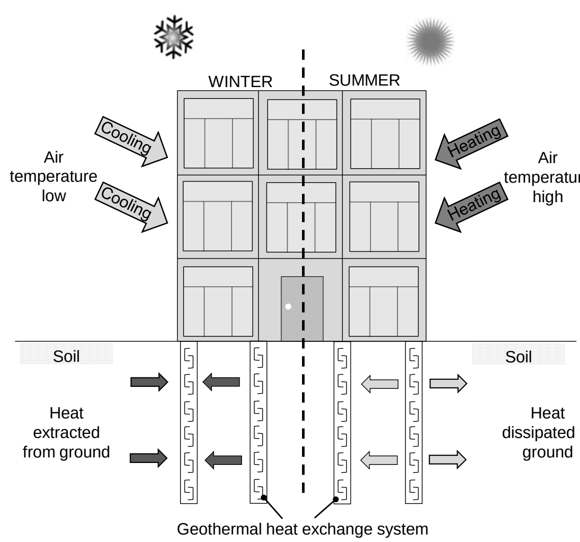

Figure 1. Concept of geotechnical energy structure.

Owing to the complexity that surrounds assessing the likely thermo-mechanical performance of energy foundations, several field investigations have been conducted in an effort to enhance understanding of thermal response of energy structures in the ground. Laloui et al. (2003) conducted heating tests on a 1m diameter energy pile embedded in saturated alluvial sandy soil under different working loads and reported heave up to 3.5 mm. The most widely reported field tests are those previously introduced at Lambeth College, London by Bourne-Webb et al. (2009). Under a working load of 1200 kN heating and cooling cycles were applied with pile head displacements fluctuating but never greater than 2 mm.

Recently several physical model studies have been conducted in the centrifuge, benefiting from the time scaling factor of N^2 (N being the applied enhanced gravity in the centrifuge) for heat flow in accelerated gravity experiments, to evaluate a greater number of thermal cycles in a shorter duration (hours) that would normally take years at full field scale. Notable centrifuge investigations include Stewart and McCartney (2014), Ng et al. (2014), Britto et al. (1989), Goode III et al. (2014) and Stewart and McCartney (2012), all of which reported observations of increased pile settlements and ratcheting over several thermal cycles. This behaviour has not yet been observed at full scale therefore thermal loading cyclic effects could become significant over longer time scales and more heating/cooling cycles in the field performance of energy structures.

Despite the valuable insight these investigations have provided into the likely thermo-mechanical response of an energy pile, it is clear that uncertainties are exacerbated by the lack of high quality monitoring data from case studies owing to practical constraints of placing measurement sensors in the soil in close proximity to the geostructure. This paper reports on a novel methodology of using transparent soil modelling, focusing on the property of refractive index and its temperature dependency, for the purpose of directly observing heat flow in soil to model thermo-dynamic problems. The experimental techniques developed are briefly described and the potential for transparent soil to model thermo-dynamic processes is demonstrated using an energy pile application; whereby, heat flow is quantified by image analysis. Detailed information regarding the development of the experimental method are fully reported in Black and Tatari (2015).

2 TRANSPARENT SOIL AND THE THERMAL VISUALISTION CONCEPT

Transparent soil consists of an aggregate and a matched refractive index fluid, when fully saturated the particles appear invisible and allow light to pass enabling visualisation through the soil. Many investigations have sought to optimise soil transparency in order to accommodate models of increased geometry and offer greater visualisation of tracking particles within the soil for displacement measurement (Black and Take, 2015). The method works by introducing a laser illumination plane in the model to highlight texture within the model that is used in conjunction with digital image correlation techniques to detect displacement (Figure 2). Pertinent works using transparent soil internal displacement measurement on routine problems such as shallow foundations, helical anchors and piles are reported by Iskander et al. (1994), Sadek et al. (2002), Gill (1999), Stanier et al. (2013), Black (2012), Forlati and Black (2014) and Black (2015).

The success of the traditional transparent soil modeling approach has long been considered to be reliant on producing a soil surrogate that offers the highest optical clarity. However, recent work by Siemens et al. (2010) and Peters et al. (2011) have embraced the loss of soil transparency as a positive characteristic for the purpose of modeling unsaturated soil phenomena in a granular transparent soil. This work reported in this paper also advocates the loss of optical clarity as a beneficial attribute of transparent soil, focusing on the property of refractive index and its temperature dependency, for the purpose of viewing heat flow in soil to model thermo-dynamic problems.

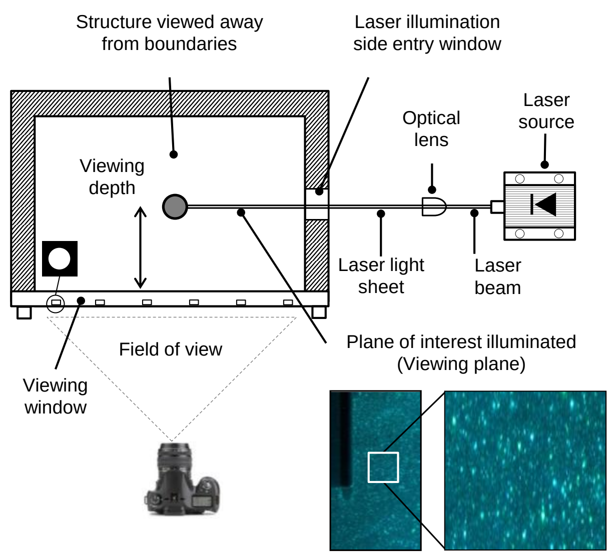

Figure 2. Transparent soil non-intrusive modelling.

Black and Tatari (2015) confirmed that temperature changes have a negative impact on soil transparency leading to the soil to become progressively more opaque as the temperature deviates from the optimum calibrated refractive index match. Referring to Figure 3 (after Black and Tatari 2015), it can be seen that when a uniform black background is placed behind transparent soil mixed at its optimum refractive match for a given temperature (i.e. calibrated at 20°C), it is clearly visible as the soil is transparent and allows the passage of light. If a digital image is captured it will contain colour intensity information stored as an 8-bit integer with a range of possible values from 0 (black) to 255 (white). Values in between these extremes describe the spectrum of shades of gray. Therefore, in the case of the target viewed through soil at 20°C, pixel intensities returned are representative of black, i.e. pixel intensity between 0 and 50. It is not uncommon in digital images that the

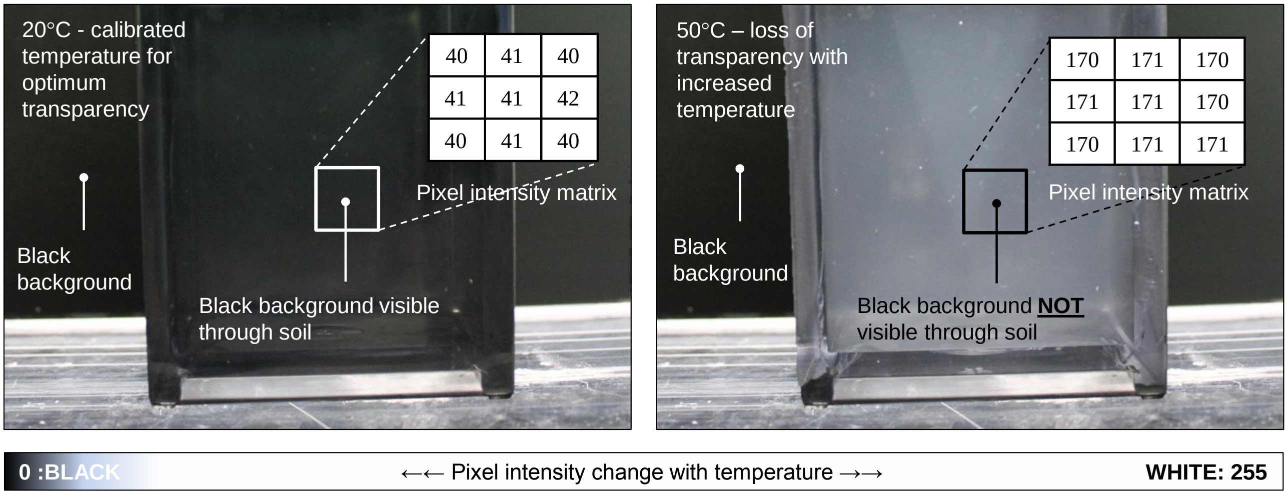

Figure 3. Concept of pixel-temperature visual based measurement for thermal modeling applications in transparent.

true colour information from a real object will not be perfectly transferred to an image due to aberrations and diffraction caused by the camera and lens, illumination conditions, or in this instance, viewing the target through a translucent medium.

Conversely, when the soil temperature is increased (i.e. to 50°C) the refractive index of the soil alters and reduces light transmission; therefore, the black target is less visible or fully obscured. In this instance the pixel intensity would no longer be close to zero, but increase such that the soil would be considered to be gray in colour. Hence, observed changes in pixel intensity provide a clear basis for a direct visual assessment measurement to detect temperature changes in transparent soil captured in digital images. The work reported herein implements this experimental methodology.

3 EXPERIMENTAL PROGRAMME

3.1 Transparent soil material

The transparent soil used in this investigation consisted of 6% fumed amorphous silica aggregate and 94% pore fluid. The pore fluid was a blend of white oil (Baylube WOM 15) and paraffinic solvent (N-paraffin C10-13) mixed to volumetric proportions of 77:23 giving a refractive index match to the silica aggregates of 1.467 at 20ºC. The particle density of the fumed silica was 2200 kg/m^3, surface area of 200±25 m^2/g and particle size D_{50} of 0.014 μm. The density of the fluids was measured to be 845.48 kg/m^3 for Baylube WOM 15 and 764.24 kg/m^3 for N-paraffin C10-13. The volumetric coefficient of thermal expansion of paraffin oil is 7.6 x 10^{-4} °C^{-1}, and 4.5 x 10^{-4} °C^{-1} for Baylube oil.

The aggregate and pore fluid were thoroughly mixed using a hand held food blender to produce a homogeneous slurry and then placed into the test chamber. Samples were located in a vacuum to evacuate the air to produce a two phase continuum and then consolidated to produce test beds having undrained shear strength of approximately 10 kPa.

3.2 Experimental equipment

The experimental system is portrayed in Figure 4. A water bath was used to provide a constant temperature boundary to the submerged soil test chamber. The water bath was filled with de-aired water that was warmed using a coil heating element and water pump that circulated the water to maintain a constant temperature. The external surfaces were covered in black card to produce a consistent background and to minimise internal light reflections in the image tests. The system was instrumented with 10 precision temperature sensors (thermocouples) that confirmed equilibrium of the water and soil temperature. These were also used to validate the pixel temperature measurement approach.

The background used to for calibration implemented in the current research consisted of a simple black uniform intensity card that was laminated to enable it to be submerged in the water bath behind the test chamber.

Images were captured using a Canon EOS 1100D Single Lens Reflex (SLR) with an 18-55 mm lens. In addition to illumination variation, pixel intensity can also be affected by camera parameters such as aperture, exposure time, and focus; hence, the camera properties were fixed at focal length of 55 mm, an aperture of F/16, shutter speed of 1/5th second, ISO of 100, auto white balance and no flash. Maintaining the constant camera settings ensured that any changes in pixel intensity detected, subsequently interpreted as a change in soil temperature, were attributed solely to loss of transparency of the soil owing to the change in its refractive index as the soil temperature changed.

The soil test chamber used for calibration and the energy pile tests measured 190 mm (W) x 150 mm (H) x 40 mm (D) and were constructed from 10 mm thick Perspex sheet. The test chamber was located in the centre of the water bath so as to provide constant temperature boundary conditions. During calibration the box contained only transparent soil and during the energy pile test the pile was embedded vertically in the centre.

3.3 Calibration of pixel intensity and temperature

Calibration of pixel intensity at various soil temperatures was achieved by submerging the soil chamber in the water bath and allowing it to be heated by the re-circulating water system in the temperature range of 20 °C to 50 ºC in 5 ºC increments. Correlation of image pixel intensity at various soil temperatures was achieved by capturing images of the calibration target placed behind the test chamber and viewed through the soil across the range of temperatures indicated. Changes in soil refractive index are recorded as changes in pixel intensities in the image that were analysed using image processing software in MatlabTM.

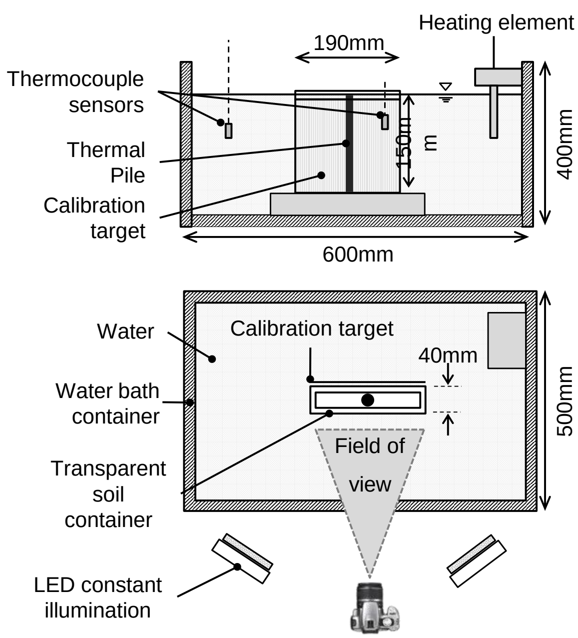

Figure 4. Transparent soil thermal modeling experimental setup.

4 RESULTS AND DISCUSSION

A number of tests were conducted to verify the experimental methodology, calibration of pixel intensity with temperature and to demonstrate the potential of this new approach of visualising heat flow directly in soil. The main objective of the paper is to validate the hypothesis that transparent soil can be used for thermo-dynamic modeling and also to demonstrate this potential by-way of a demonstration application. In this regard the modelling approach is applied to an energy pile example.

4.1 Calibration of test system

The test environment was calibrated by increasing the temperature of the water and logging the response time to ensure steady state heat conditions were maintained. It was determined that the water reached and the desired temperature in approximately 200 minutes and was able to maintain this to within ±1°C degree during the test programme. Ensuring a constant test environment was crucial to the success of the temperature-pixel based measurement concept proposed.

4.2 Pixel intensity and temperature relationship

Despite the level of control employed in the current investigation, small variations of up to 10 pixels were observed in pixel intensity measurements across the calibration target. This was owing to small internal reflections within the water bath caused by the ambient illumination conditions provided. Any variation in pixel intensity will have a detrimental effect on the interpretation of temperatures using an image based measure detection system. Hence, pixel intensity normalization was conducted to account for the small anomalies observed at each pixel location using the minimum and maximum intensities determined for images at the extreme temperatures of 20 °C and 50 °C according to Equation 1

$$PI_N = \frac{PI - PI_{min}}{PI_{max} - PI_{min}} \quad [1]$$

where PI_N is the normalised pixel intensity, PI is the captured intensity at a given temperature, and PI_{min} and PI_{max} are the minimum and maximum pixel intensity recorded at 20°C and 50°C respectively. This normalisation was implemented for each temperature increment such that the normalised pixel intensity of the soil varied from 0 to 1 for temperatures of 20°C and 50°C respectively and is shown in Figure 5.

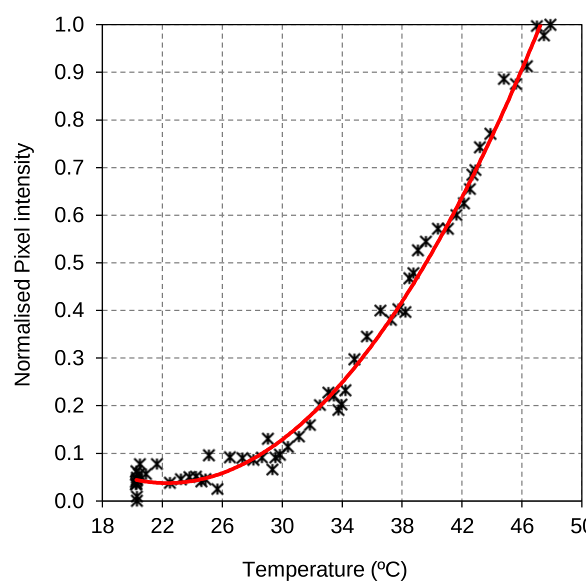

Figure 5. Normalised pixel intensity with increasing soil temperature.

Although non-uniform, a strong correlation exists between the normalised pixel intensity and temperature. It is also interesting to note that the trend line turning point corresponds to the temperature at which the material was calibrated to yield optimum transparency (i.e. 20°C)

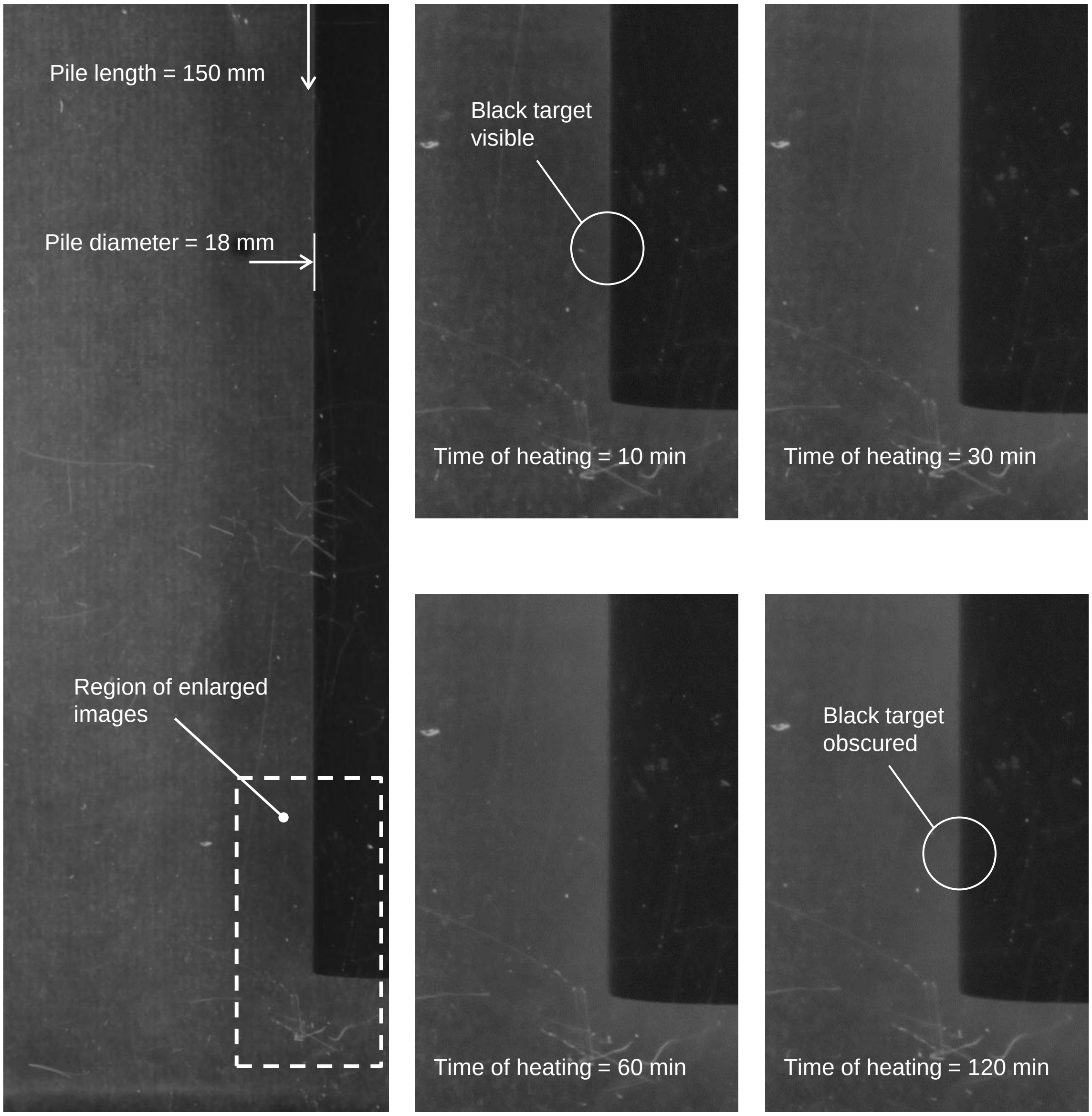

Figure 6. Change in transparency around the pile with increased heating time at 20°C.

which is in good agreement with previous research reported by Stanier (2011) and Black and Take (2015) into optimum transparency conditions. On this basis it is confirmed that transparent soil offers to potential to model thermal problems in soils.

4.3 Energy pile application

The emerging application of an energy pile has been selected to demonstrate the potential of transparent soil and this newly established relationship to model thermo-dynamic processes. The model energy pile was machined from aluminium and measured 18 mm diameter (d_0) by 150 mm long. A cartridge heating element of 100W capacity, measuring 6.5 mm in diameter x 70 mm long, was inserted in a bored recess in the centre of the pile and fixed in place using thermal epoxy. The pile was sprayed matte black to minimise reflections into the soil and also ensure that changes in pixel intensity at the pile-soil interface would be clearly identifiable.

Energy pile tests were conducted by increasing the temperature of the pile to 50ºC while maintaining the temperature of the water bath at 20ºC. Typical in-situ ground temperatures are in the range of 10ºC to 15ºC, thus the selected valued of 20ºC is slightly higher than what may normally be expected but not unreasonable.

The impact of temperature change and heat flow is examined vertically in the middle of the test chamber along the edge of the pile over its length. The effect of temperature on the transparent soil is shown in Figure 6 at time intervals of 10 min, 30 min, 60 min and 120 min. It is evident in the images that the soil in the immediate proximity to the pile became gradually more opaque with

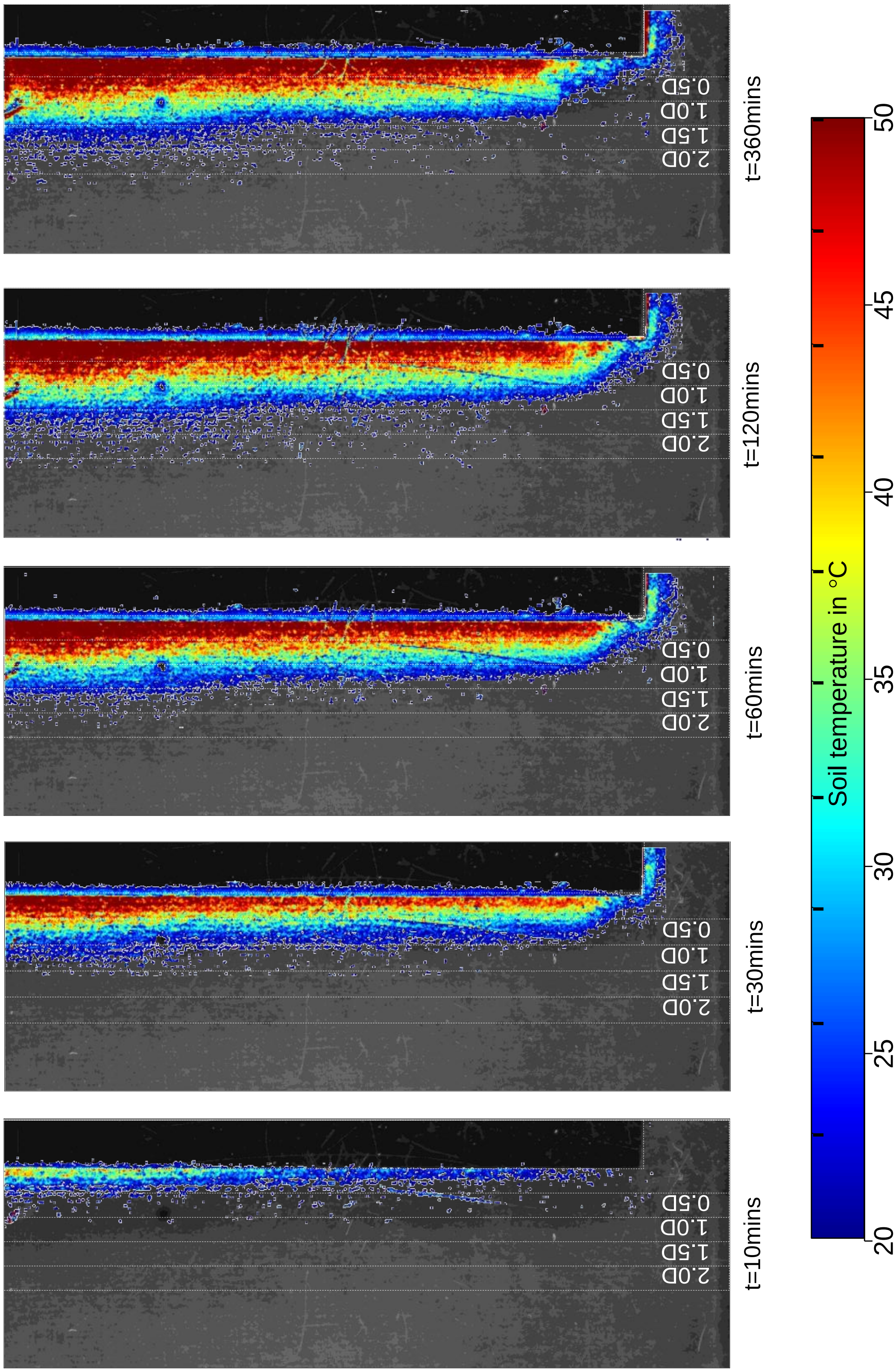

Figure 7. Horizontal heat flow visualized in transparent soil along the pile length for a 20°C to 50°C heating cycle at time intervals t = 10, 30, 60, 120 and 360 min depicted as a thermal heat map.

increased time as the heat flow propagates through the soil material away from the pile heat source.

Figure 7 presents analysis of the soil temperature response for an energy pile vertically embedded in the soil during which the temperature of the pile was activated and increased to a constant temperature of 50 °C. Data is presented at time intervals of 10 min, 30 min, 60 min, 120 min and 360 min; whereby radial distance away from the pile centreline and depth are normalised by the pile diameter. The heat map shows regions of varying soil temperature and is presented in °C by converting the recorded image pixel intensities using the previously established relationship for normalised pixel intensity and temperature.

Horizontal heat flow propagating radially from the pile is clearly evident. At t=10 min only a small region of soil to a depth $z/d_0 = 3$ exhibits an increase in temperature of approximately 35 °C. This corresponds to the location of the internal heating element embedded in the pile that extended to a depth corresponding to $z/d_0 = 4$. Significant changes are observed with longer heating exposure time whereby increased soil temperature is clearly evident along the entire length of the pile. Some small temperature rise is also registered at the pile base. It is also interesting to note that greater thermal heating continues to occur in upper region of the pile near the heat source. A clear thermal gradient is established at t = 30 min whereby the temperature at the pile-soil interface is the same as the pile at 50 °C, and decreases with distance from the pile centreline to the ambient soil background temperature of 20 °C that is maintained by the water bath boundary condition. The extent to which this heating zone extends continues to grow up to t = 120 min at which point no further changes were detected. The zone of heating in the soil at the steady state conditions varies slightly along the pile depth from approximately $r/d_0 = 1.5$ up to a depth of $z/d_0 < 3$, to $r/d_0 = 1.0$ at $z/d_0 > 7$.

It is these observed changes in soil temperature along the length of an energy pile that have been postulated by, Bourne-Webb et al. (2009) and Brandl (2006) as the likely contributing factor for increased foundation movements in geothermal structures due to changes in side friction characteristics arising from thermal expansion and contraction of the soil.

Bourne-Webb et al. (2009) reported that the temperature recorded in a borehole positioned 0.5 m from the energy pile halved at a radial distance equivalent to $r/d_0 = 1$ and at $r/d_0 = 1.5$ changes where negligible. Cui et al. (2011) reported $r/d_0 = 1.2$ for the zone of influence from a numerical analysis of a pile geothermal heat exchanger. Similar zones of influence are observed in the present work although it should be noted that scaling of heat flow from small scale models to prototype field conditions is highly complex and more fundament investigations on the thermal scaling laws of transparent soil are required.

CONCLUSIONS

An alternative experimental method using transparent soil and digital image analysis is presented for the purpose of visualising heat flow in soil. The work explored and verified the hypothesis that temperature changes in transparent alter its refractive index and therefore progressively reduce its transparency becoming more opaque. The development of the experimental methodology was discussed and a relationship between pixel intensity and soil temperature is defined and verified. This relationship is applied to an energy pile example in heating mode to demonstrate and visualise heat flow in soil. The heating zone of influence is observed to extend to a radial distance of 1.5 pile diameters which reflects similar values reported in literature from field and numerical investigations. The paper reports on the successful implementation of this technique which provides a new paradigm for transparent soil to potentially contribute to greater understanding of thermo-dynamic processes in soil.

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