EXPERIMENTAL ANALYSIS OF HEAT TRANSFER IN SOIL AT DIFFERENT WATER TABLE LEVELS

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ABSTRACT
The demand for energy consumption is substantial in countries with cold climates, comprising more than 30% of total energy according to the International Energy Agency. Heat loss into the ground layers through the building's partition alters the naturally established thermal equilibrium between the atmospheric air and soil layers in winter. Here, the heat dissipation process in the layers of the soil was experimentally investigated at low and high water table levels. The first part of the experiment research included heat transfer from a heating device into the ground. The second part monitored the heat dissipation process in the soil layers until the initial natural thermodynamic equilibrium was attained. A heating device was built and installed in the clay at a depth of 1 metre from the ground surface with a temperature equal to the thermal comfort of the inside building, 20°C. The temperature of the soil layers started to transform from the initial temperature lower than 5°C. It reached a new thermal equilibrium after six days of heating with a stable heat flux value of 117 W/m^2. This value describes the heat loss to the atmosphere to maintain a new thermal equilibrium. The temperature of the soil layers returned to the initial value on average two weeks after the heating device was turned off. The investigation has given the ability to analyse the possibility of soil usage for thermal accumulation. The research methodology was tested and analysed for further research on the thermal charging and discharging of the soil and its ability to retain heat for a longer duration.
Keywords: heat transfer in the ground, temperature distribution, thermal equilibrium, water table, heat accumulation.

1 INTRODUCTION

In the colder regions, such as northern countries, the energy consumption for heating the buildings constitutes a substantial portion of the total energy. This dependency on heating the space can vary significantly, typically ranging from 40% to 70% during the cold periods [1]. The building's architecture, its structural materials, the local climate conditions, the type of energy source used for heating, and its efficiency are factors contributing to the energy consumption for heating [2]. The temperature of the building structure and the indoor air are elevated to create a warm and comfortable environment for the occupants. However, a portion of the energy utilised for heating is lost to the environment: the atmosphere and the ground [3]. Heat lost through the building's partition into the ground not only impacts the energy efficiency but also influences the thermal equilibrium of the ground below and surrounding the building, as the soil temperature is lower than that of the heated building [4]–[6]. To improve energy efficiency and maintain a consistent temperature profile within the residential building, it is important to address heat loss through the building partition. The research was performed to analyse ground and the dissipation of heat through different soil layers with varying levels of the water table [7], [8].

The thermal conductivity of the soil varies well with the proportion and heat conductivity of the solid, air, and water [9]. One of the factors that significantly affects the heat transfer in the soil is its varied moisture content [10]. Air temperature, wind speed, solar radiation (direct and diffuse short-wave), relative humidity, precipitation, and vegetation affect the moisture content and subsurface ground temperature. Evaporation and precipitation levels directly impact the moisture content of the surface [11]–[13]. The quantity and condition of

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the moisture content influence the heat transfer in the soil because water has a higher thermal conductivity than soil, which means that it can elevate the heat transfer more easily [14], [15].

Heat dissipation through the adjacent layers of the soil was experimentally researched in the field conditions [16], [17]. The experimental simulations of the heat transfer through the partition of the building into the ground and the increase in soil temperature were performed. This research focuses on the analysis of the formation of the new thermo-dynamic equilibrium while the soil was heated and the return to natural conditions at the stopped ground heating.

2 METHODOLOGY AND EXPERIMENTAL SETUP

When a building loses its heat from its partition to the ground, it increases the temperature of the ground. Increasing ground temperature changes natural thermal equilibrium. The heat transfer from the external partition of the building to the soil was investigated experimentally. It was assumed that thermal comfort was maintained inside the building, and a part of the heat was lost through the walls or floors, transferring into the ground. Each experiment was divided into two phases. The initial phase focused on heat transfer to the ground until a new thermal equilibrium was reached. Subsequently, the second phase involved monitoring the heat dissipation across the adjacent layers of the soil. It continued until the temperatures of the ground layers returned to the initial natural thermal equilibrium after the heating device was off.

A heating cable CTAV-18 heating cable was mounted evenly onto the wooden board with a thickness of 0.01 m. A steel plate was used to construct the heating surface of thickness 0.001 m. The length and width of that surface were equal to 0.50 m. The thermal insulation layer, polystyrene EPS 70 NEO with a thickness of 0.1 m was placed on the top of the heating device. And it was buried in the ground at 1 m depth, beneath a layer of clay. In the case of moist clay with a water content of 50%–90% (case 1), the thermal conductivity (λ), specific heat capacity (c_p), and density (ρ) of the clay at a depth of 1 m were; λ= 0.5–1.5 W/(m.K), c_p = 1500–2000 J/(kg.K), ρ = 1800–2200 kg/m^3, respectively [16], [17]. And in the case of fully saturated (cases 2, 3 and 4), λ= 1.0–2.0 W/(m.K), c_p = 2100 J/(kg.K), ρ = 1400–2100 kg/m^3 [16], [17]. The heating surface was orientated downward, resembling the case of heat loss from the basement. The soil temperature was measured using platinum resistance Pt1000 (class A precision) and placed at the centre of the heated surface, at the distance of 0.25 m and 0.50 m from the heating device, as shown in Fig. 1. The electric resistance of the thermometers was recorded and sent to the computer by Logger PT-104. The temperature of the heated surface was kept constant using the ATR244-12ABC controller. The voltage was measured using a multimeter, ESCORT 3136A, at the connection of the heating cable. The second input of this device was used for the electric current measurement. During the experiment, the power of the device was equal to P = 375±10 W.

A heating device was used to charge the soil by turning it on and off for each interval. The average charge intensity (heat flux density) for each interval was computed using the equation:

$$q_{av,h} = \frac{\sum_{m=1}^{k} P_m t_m}{A t_s}, \tag{1}$$

where $q_{av,h}$ is the average charge intensity, m is the number specifying a particular charge, k is the number of charges per set time interval, P_m is the power of the particular charge (calculated from the electrical parameter of the heating device), t_s is the time interval for which the average heat flux density was calculated. A is the area of the heating surface (0.25 m^2) and t_m is the duration of a particular charge.

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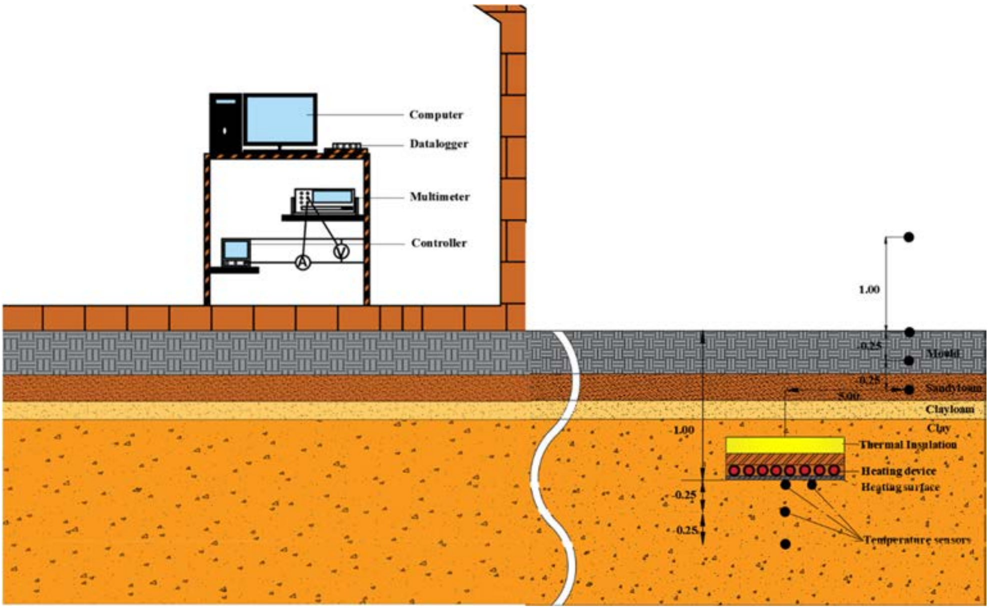

Figure 1: Experimental setup in field condition.

Also, it was assumed that the consumed electricity was equal to the amount of heat generated. The heat (Q) required to warm up each component of the experimental setup till the set temperature (T_s) was aggregated and eliminated from the total heat charged into the soil.

$$Q = \sum_{l=1}^{r} m_l C_{pl} (T_s - T_o), \tag{2}$$

where Q is the heat required to warm the experimental device, m is the mass, C_p is the specific heat, l is the number specifying each part of the experimental setup, and r is the number of the parts of the device.

3 RESULTS OF THE EXPERIMENT

The experiments were divided into four cases and carried out in Kaunas, Lithuania. The investigation began in the early winter and ended in early spring. The heating device was placed at a depth of 1 m in clay soil of known thermal properties. The heating device was maintained at 20°C. The initial soil temperature at 1 m depth for cases 1, 2, 3 and 4 is 7.0°C, 5.5°C, 5.1°C, and 4.4°C, respectively and the temperature of the air was in the range of −2.8°C to −5.7°C. The water table was at a depth of 1.6 m from the ground surface in case 1. In the second, third, and fourth cases, the water table increased to a depth of 0.9–1.0 m from the ground surface. During the investigation at the site, the snow was occasional and short-lived, and was not feasible to observe the influence of snow on the heat dissipation process.

The controller operated discretely, turning the heating surface on at the set temperature of 20°C and off at 20.2°C. The elevated temperature of the heating surface influenced the heat transfer from it to the colder ground. This process resulted in the warming of a layer of soil near the surface, initiating a subsequent transfer of heat to deeper layers of soil. When the heating cable was connected to the electricity and operational, it was referred to as being charged. In case 1, the first charging period lasted 559 s, the second 85 s, and the third 69 s. Gradually, the charging time approached 43 s. As the temperature of the soil increased, the disconnected heating device resulted in longer intervals between the charges, as shown in Fig. 3. During the first six hours of heating in case 1, the soil temperature has increased from $T_{1.25}$ = 7.59°C to $T_{1.25}$ = 8.50°C at a depth of 1.25 m, from $T_{1.50}$ = 8.30°C to $T_{1.50}$ = 8.33°C at a depth of 1.50 m (Fig. 2). The average heat flux density of the first hour was equal to 430.7 W/m^2, and of the second 185.8 W/m^2. With the increase in the soil temperature, the condition for charging the soil became less favourable. The average hourly heat flux density decreased to a value of 108.8 W/m^2 at the end of the first day of charging. The average heat flux density for the first day was equal to 133.04 W/m^2.

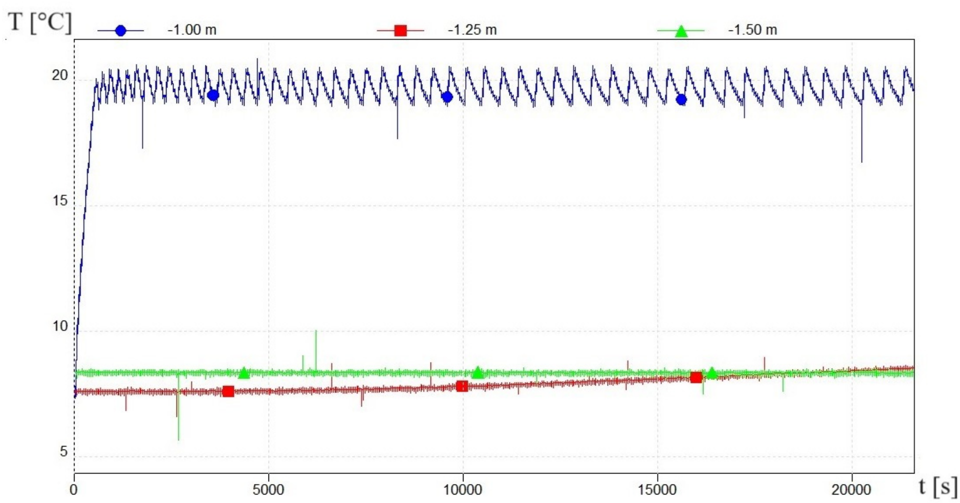

Figure 2: Soil temperature change over first six hours at 1.25 m and 1.5 m depth in case 1.

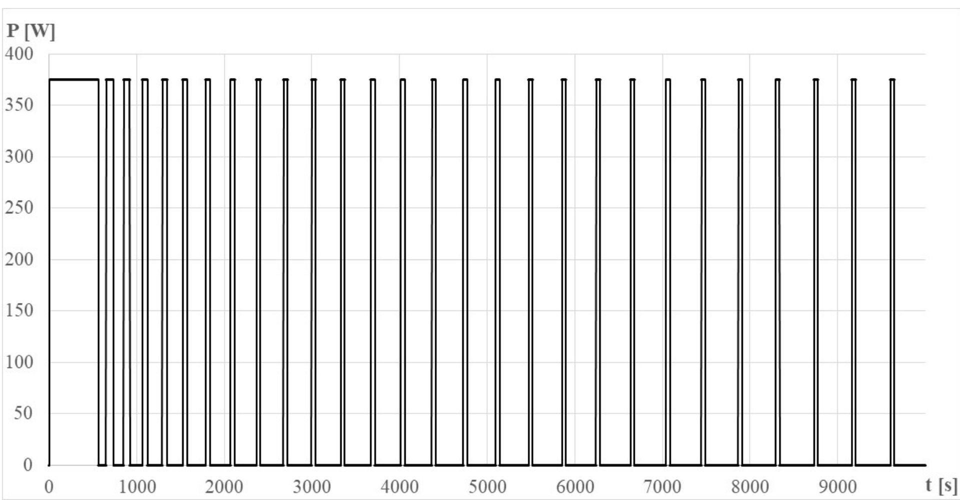

Figure 3: Power of heating device of each interval of charges for first three hours.

The average hourly heat flux density was calculated for the first day, as shown in Fig. 4. It was observed that case 3 exhibited the highest heat flux density of 643.3 W/m^2, followed by cases 4 and 2 of 615.3 W/m^2 and 591.1 W/m^2, respectively during the first hour. On the contrary, Case 1 differed greatly from the other three cases, displaying a heat flux density of 430.7 W/m^2. However, this phenomenon cannot be explained only by the difference in initial temperature. Here, the influence of the water table was observed. The ground was fully saturated in cases 2, 3 and 4, increasing its specific heat capacity. Therefore, more heat is required to charge it.

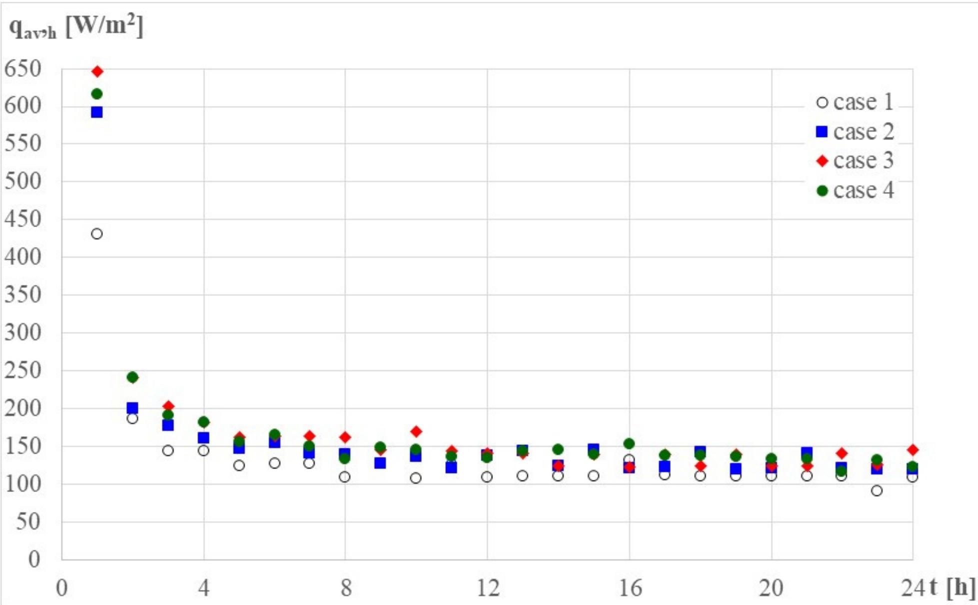

Figure 4: Average hourly heat flux density of each case for first 24 hours.

The velocity of heat propagation, which means that the sensor to the change in temperature, was observed at a depth of 0.25 m from the heating surface in each case. The results revealed that the time taken to reach the mentioned sensor in cases 2, 3 and 4 was 4355 s, 3516 s, and 4933 s, respectively. And it was 689 s slower in case 1 than that in other cases. This can be explained by a higher thermal conductivity in the case of fully saturated soil. The temperature change was observed at the depth of 0.5 m from the heating surface as well. In case 1, the temperature change was noticed after 24,440 s. In cases 2, 3 and 4 it was observed at 22,271 s, 22,623 s, and 22,270 s, respectively. This reveals that the velocity of heat propagation decreases with an increase in distance. Furthermore, there was less temperature difference between adjacent layers, heat dissipation to the sides, and heat was carried by groundwater. A steady value of temperature was observed after a time interval. Case 4 was dedicated to this. Here, the thermal equilibrium was reached after six days, and the constant value was equal to 117.4 W/m^2 (Fig. 5).

Now, the heating device was turned off, but the heat continued to dissipate, awaiting the natural equilibrium of the temperature distribution. Temperature variation, calculated as

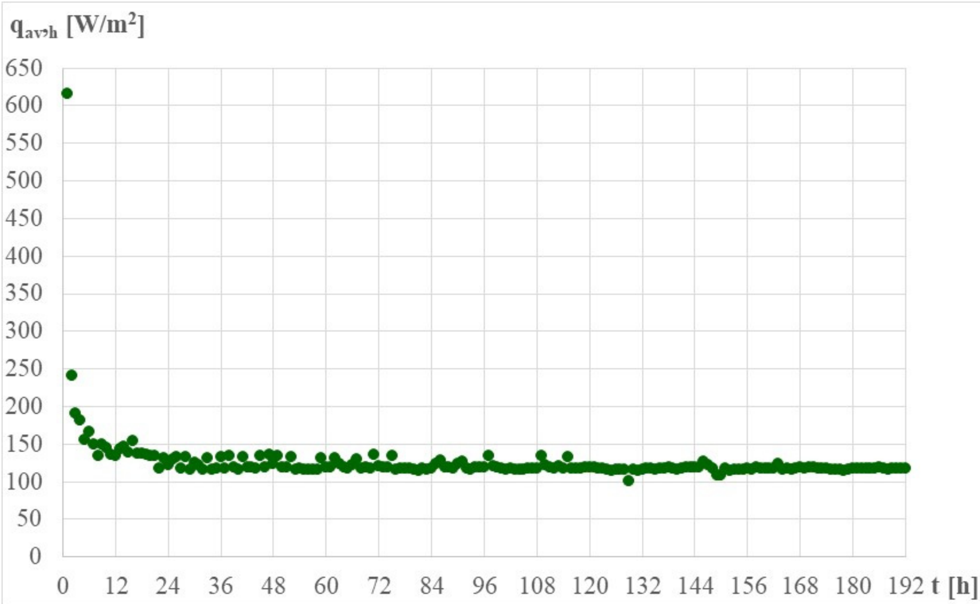

Figure 5: Constant average hourly heat flux density after six days (case 4).

temperature difference of each day, ($\Delta T = T_{24:00} - T_{00:00}$) at the depths of 1.00 m, 1.25 m, and 1.5 m are shown (Figs 6–8). The heat dissipation process was observed over approximately one week in the first two cases. This duration was extended to two weeks in cases 3 and 4. The difference in the temperature value at 1.00 m, 1.25 m, and 1.50 m on the first day including all the cases shows that the heat dissipation was slower in case 1. Furthermore, the heat stored near the heating device surface was hotter than the other nearby soil layers. This resulted in a rapid cooling delay. This was observed on the first day at a depth of 1.50 m. In addition, the highest temperature difference at a depth of 1.50 m on the second day shows the most significant heat loss. Finally, the natural equilibrium was achieved in about two weeks. Here, the manner heat moves from the heating surface to the layers of clay saturated with water at a depth of 1.00 m was analysed. The heat flowed downward, and the change in the heat flux was calculated in the short vertical distance; heat dissipation to other directions was not analysed.

4 CONCLUSIONS

The research contributes to Agenda 2030 by addressing the goals related to ‘Affordable and Clean Energy’, ‘Sustainable Cities and Communities’, and ‘Climate Action’, and their targets of ‘double the global rate of improvement in energy efficiency’, ‘reduce adverse per capita environmental impacts of cities’ and ‘integrate the climate change into national strategies, planning and policies’ by 2030, respectively.

The experimental investigation focused on analysing the heat transfer into the soil, including the charging of the ground, dissipation of heat, and the formation of thermodynamic equilibrium. A high level of the water table resulted in soil saturation, increasing both the specific heat capacity and thermal conductivity, and intensifying the heat transfer. The average hourly heat flux density was equal to 617 W/m^2, during the first hour for high water table levels. In contrast, it was 431 W/m^2 with a low water table level.

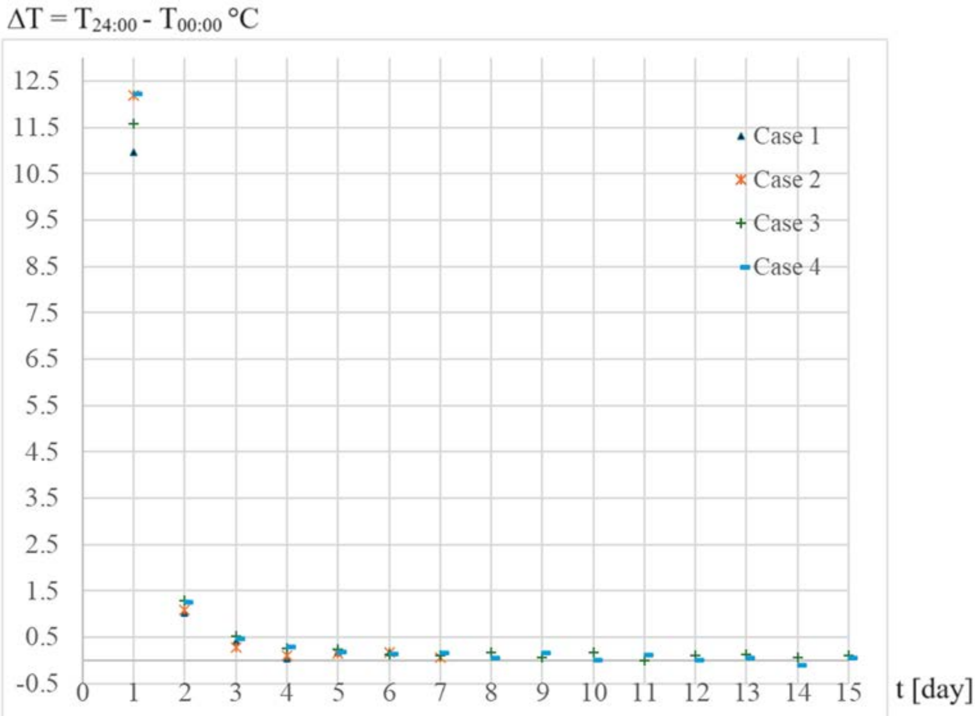

Figure 6: Temperature difference of each day at a depth of 1 m.

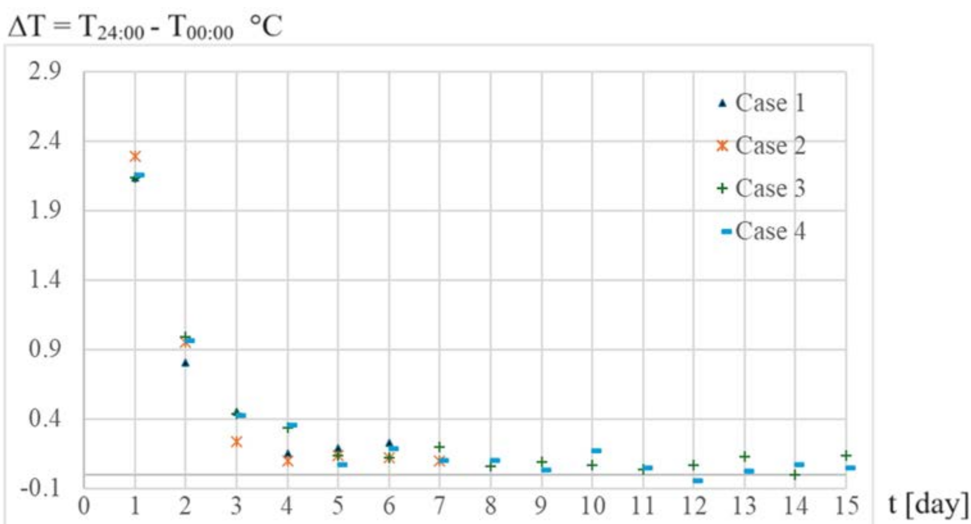

Figure 7: Temperature difference of each day at a depth of 1.25 m.

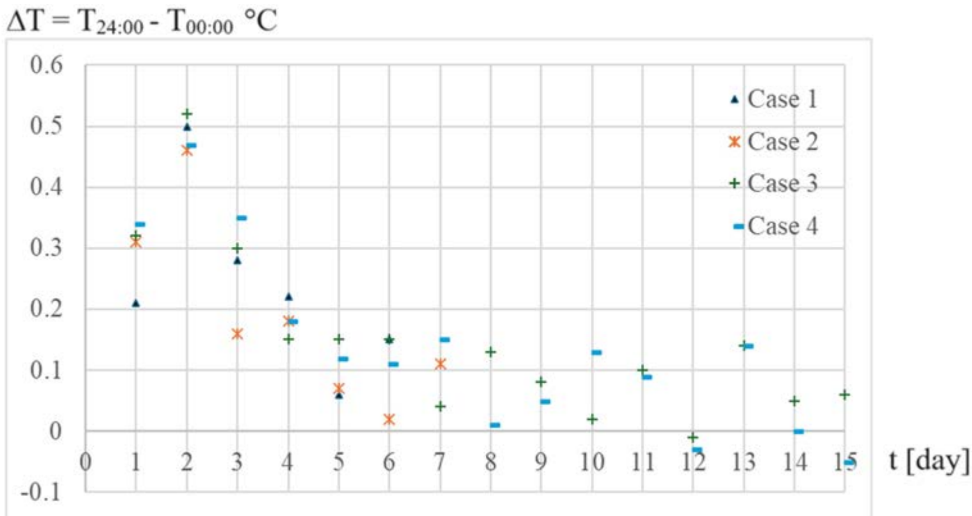

Figure 8: Temperature difference of each day at a depth of 1.5 m.

After six days of heating, the temperature was stabilised at a dynamic thermal balance from an initial temperature of 4.4°C. The heat from the experimental equipment at a depth of 1 m compensated for the heat dissipation in the fully saturated clay. The average hourly steady heat flux density was equal to 117.4 W/m^2. After the heating was turned off, the initial thermal balance was reached after two weeks.

Hence, the results of the research offer a potential application in optimising the soil to efficiently dissipate excess heat from hybrid solar modules, solar collectors, or other devices.

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