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An Empirical Estimation of Underground Thermal Performance for Malaysian Climate

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Abstract. In this study, the soil temperature profile was computed based on the harmonic heat transfer equations at various depths. The meteorological data ranging from January, 1st 2016 to December, 31st 2016 measured by local weather stations were employed. The findings indicated that as the soil depth increases, the temperature changes are negligible and the soil temperature is nearly equal to the mean annual air temperature. Likewise, the results have been compared with those reported by other researchers. Overall, the predicted soil temperature can be readily adopted in various engineering applications in Malaysia.

1. Introduction

Soil is not a good insulator for underground structure: the resistance of heat flow of dry earth is less than 15% of that of moisture and decreases rapidly when the moisture content increases. However, the soil is a terrific moderator for temperature fluctuations [1] in which it does not respond to daily temperature variations and only reacts gradually to seasonal changes. Due to the high thermal inertia (51% of the energy from the sun absorbed by the soil as shown in Figure 1) and the great heat capacity of the soil structure, it allows a damping of surface temperature fluctuations at a rate that varies exponentially with respect to the soil depth [2]. In other words, at a sufficient depth, the soil temperature is lower than the surface air temperature during daytime (the trend is opposite during night-time). Therefore, soil temperature is seemingly a key factor in affecting the heat transfer of an underground building and the thermal storage for new sources of renewable energy [3–7]. Therefore, the investigation of soil temperature at different depths is necessary to calculate the heat flux through the building surface. Meanwhile, the soil temperature data can be used for designing underground building in Malaysia.

Soil temperature has been investigated for different geographical locations [8], geothermal assessments [3,9] and soil depths [9–11]. Also, research work on Ground Heat Exchanger (GHE) implementation [12,13], underground building [5,6,14] and underground wine cellar [2,15] have been performed as well. According to the papers above, the research of soil temperature variation within a tropical climate region is still incipient. Alam et al. [16] applied the soil temperature variation in designing an energy-efficient green building in Malaysia. However, the climate data in China was implemented directly in Malaysia environment. Yusof et al. [4] investigated the potential of ground cooling in Malaysia by using weather data measured in Kuantan, Pahang. However, the data provided by Yusof et al. [4] was limited to the soil depth of up to 6m only, which is not readily applicable in designing underground building in Malaysia. In the present work, an equation was established to determine the soil temperature for Malaysian climate. The analysis included the investigations of high



and low dry bulb temperatures, average dry bulb temperature, amplitude of surface temperature and mean annual air temperature. In addition, the phase constant (the minimum surface temperature throughout the year) was investigated as well. All analyses were performed by using the climate data provided by the Malaysian Meteorological Department for station 48684. It is worth to mention here that our proposed correlation considered the soil depth of up to 15m.

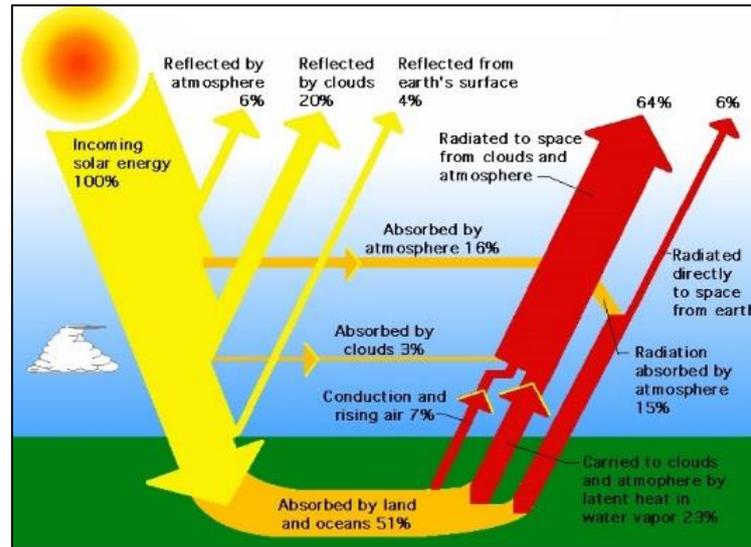


Figure 1. Earth energy balance

2. Method

2.1. Study area

Malaysia is a maritime country close to the equator which lies between 1° and 7° North latitude and 100° and 119° East longitude. It consists of west and east regions separated by the South China Sea. As a tropical country, Malaysia experiences high temperature and relative humidity, light and variable wind conditions and long hour of sunshine with rainfall occurred throughout the year. The average sunshine is around 6 hours. The daily temperature in Malaysia ranges from 24°C to 38°C. The lowest temperature is usually recorded during night-time. The mean daily humidity can be as low as 42% to as high as 94%. The annual evaporation rate in Malaysia is about 4mm–5mm per day depending on the cloud cover and the air temperature. Due to its hot and humid climate, cooler days are generally exhibiting lower evaporation rate and higher relative humidity as compared to warmer days [17]. In the present study, the soil temperature in Petaling Jaya, Selangor, Malaysia was investigated.

2.2. Numerical simulation

The soil temperature can be affected by variables such as topography, meteorology and sub-surface. Basically, the energies from meteorology elements such as solar, atmospheric agents and air are continuously transmitted to the soil surface (see Figure 1). Solar energy is the most dominant factor. In addition, daily and seasonal changes in solar energy will inflict a cyclical variation in air and soil temperatures. Other factors such as wind and rain could cause local variations as well. The typical annual temperature variation at the surface (or close to the soil surface) follows the pattern of simple harmonic equation. This harmonic equation can be modelled based on the Kasuda model [8], where the soil temperature is a function of time (day), soil depth and air temperature:

$$T(z, t) = T_{mean} - \left[\left(T_{amp} e^{-z \left(\frac{\pi}{365\alpha} \right)^{1/2}} \right) \cos \left\{ \left(\frac{2\pi}{365} \right) \left((t - t_0) - \left(\frac{z}{2} \right) \left(\frac{365}{2\alpha} \right)^{1/2} \right) \right\} \right] \quad (1)$$

Here, $T(z, t)$ is the undisturbed soil temperature at time t (day) and depth z (m), T_{mean} is the mean surface temperature, T_{amp} is the amplitude of surface temperature, α is the thermal diffusivity of the soil (m^2/day) and t_0 is the day of the year with minimum surface temperature. T_{mean} , T_{amp} and t_0 can be determined from the meteorology data. However, α should be determined based on the physical soil characteristic such as soil type and moisture content.

2.3. Data Analyses

In order to apply Eq.(1) for Malaysia climate, the data provided by the Malaysian Meteorological Department was used. The data has been generated hourly starting from 0001H 1st January 2016 until 2359H 31st December 2016. Table 1 shows the monthly average temperature (derived from the hourly temperature).

Table 1. Climate Data for Petaling Jaya

Month	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Yearly
Record High													
Dry Bulb Temp (°C)	35.90	35.70	36.20	36.90	36.20	35.70	35.80	34.80	34.80	34.20	34.10	35.10	36.90
Record Low													
Dry Bulb Temp (°C)	23.80	25.00	23.70	24.60	23.40	23.40	27.41	23.80	28.01	23.60	23.30	22.50	22.50
Ave Dry Bulb Temp (°C)	29.13	29.19	29.99	30.13	29.23	28.96	28.59	29.51	28.84	28.70	27.51	27.67	28.95
Amplitude of Surface Temp (°C)	5.99	6.18	5.82	7.20	6.39	7.49	7.92	4.92	6.56	6.10	5.64	7.50	6.48

From Table 1, the lowest and highest temperatures are 22.50°C and 36.90°C, respectively. The temperature amplitude is 6.48°C and t_0 is taken from the basis of daily average temperature as shown in Figure 2. Meanwhile, the mean annual air temperature is 28.95°C. The thermal diffusivity, α is 0.06 m^2/day with R^2 value of 0.9999 [4]. Substituting the above-mentioned values into Eq. (1), the soil temperature can be predicted as:

$$T(z, t) = 28.95 - 6.48 e^{(-z \times [\frac{\pi}{366\alpha}]^{0.5})} \cos \left[\frac{2\pi}{366} (t - 169) - z \times \left[\frac{\pi}{366\alpha} \right]^{0.5} \right] \quad (2)$$

The soil temperature, which is generated from MATLAB software, is applicable up to soil depth of 15m. The results are shown in Figure 3.

3. Result and Discussion

3.1. Soil temperature measurement

Figure 3 shows the time history of temperature distribution for various depths calculated from Eq. (2). It seems that the soil surface temperature remains in phase with that of the daily temperature in Figure 2. However, at the soil depth of approximately 1m, the temperature fluctuation, which is previously observed near the soil surface, is diminishing. At the soil depth of 5m, the maximum soil temperature condition occurs during the first 6 months of year 2016. However, the temperature is almost constant for soil depth of 10 m and beyond, and the soil temperature is nearly equal to the mean annual air temperature of 28.95°C. It is believed that soil which is high in thermal inertia would induce temperature fluctuation. Meanwhile, factors such as time lag and temperature fluctuation between the surface and

the soil could cause the soil to become isothermal after it reaches certain depth. These findings are consistent with those reported by previous researchers [3–6].

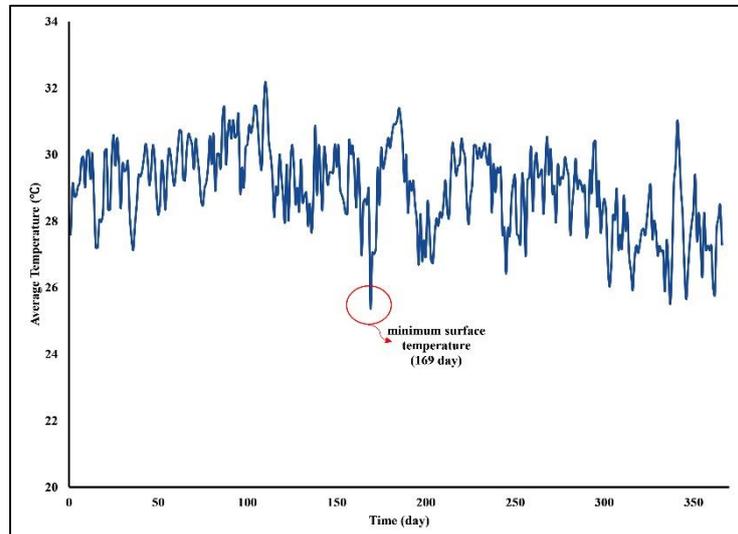


Figure 2. Daily average temperature of 2016

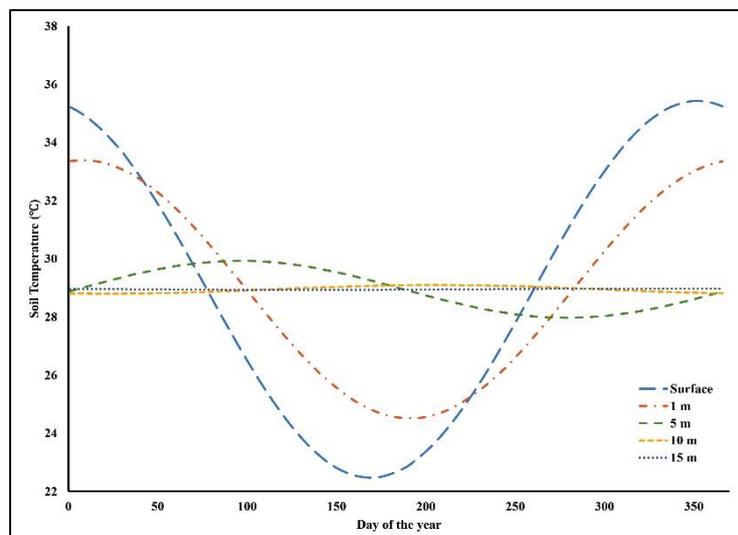


Figure 3. Soil temperature distribution at various depths throughout the year

3.2. Comparative analysis of other literature

The result has been compared with those reported by [4,18]. The meteorological data was analysed according to their respective local weather conditions. The soil depth and the thermal diffusivity were 4 m and $0.05 \text{ m}^2/\text{day}$, respectively. Table 2 indicates the values for all variables in Eq. (2). Figure 4 compares the results obtained from the present study and other references. The analysis was conducted using MATLAB software. From Table 2, the present mean annual air temperature is slightly higher than the others. Ref [18] reports a greater value of temperature amplitude. As shown in Figure 4, the harmonic pattern predicted from the present study is completely different from those reported by [4,18], even though the local weather conditions reported in Ref. [4] are quite similar to those considered in the present study. The only discrepancy between Ref. [4] and the present study was the measurement location of weather data. However, all results show that as soil depth increases, the soil temperature is

converging to the annual mean air temperature. To the best of the authors' knowledge, it is believed that the phase constant plays a major role in producing the harmonic pattern of heat transfer at various depths. In addition, thermal diffusivity also plays an important role in the annual soil temperature variation.

Table 2. Variables data for each case

Variables	Al-Ajmi et al. [18]	Yusof et al. [4]	Present Study
T_{mean} (°C)	27	26.9	28.95
T_{amp} (°C)	13.3	5.7	6.48
t_0 (day)	16	365	169
α (m ² /day)	0.05	0.05	0.05
Location	Kuwait	Malaysia	Malaysia

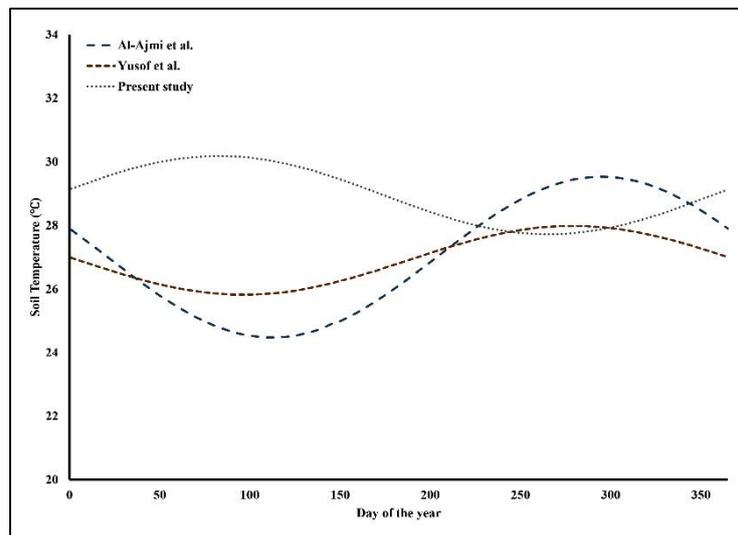


Figure 4. Comparison analysis of soil temperature

4. Conclusion

In this study, the soil temperature has been determined from the Malaysia meteorology data. An empirical equation has been proposed. At a depth of 10 m and beyond, the soil temperature is constant which is equal to the mean annual air temperature. The present results can then be used to calculate the heat flux through the underground building structure in Malaysia. Subsequently, the thermal performance in an underground building can then be determined accurately.

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