Soil Temperatures Regime at Ahmedabad

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Abstract

A 3-m deep temperature probe was installed at the campus of Indian Institute of Management, Ahmedabad in August, 1999. Probe has five resistance type device PT 100 sensors, mounted at 1-m interval. It was put in to the ground up to depth of 3-m. First sensor is at 3-m depth, second at 2-m depth, third at 1-m depth, fourth just 2 cm below the surface and the fifth 1-m above ground. Temperatures from all the sensors were noted one day on each month for a year. Readings were noted at hourly interval. In this paper, the results are presented. Motivation for this work was the need to know the diurnal and seasonal variation of temperature in deeper layers of soil in order to determine the level suitable for installation of earth tube heat exchangers.

Introduction

We have been developing **earth tube heat exchangers (ETHE)** for space cooling in parts of Gujarat. This required knowledge of soil temperature regime and the variation in it through the year. ETHE needs to be buried at a depth where diurnal as well as annual fluctuations in temperature become small. For ETHE meant for long hours of continuous operation, greater depth is desirable. Temperature data of deep layers of soil is not available for any site in Gujarat. Measurements do exist for some other part of the country, for instance, Jodhpur **[1]**, Pantnagar **[2, 3]**, and Ludhiana **[4].** These go up to the depth of 1.75 to 2.0 m. Our interest lies in deeper levels. Accordingly, we developed a 3-m deep temperature probe and installed it at the campus of IIM, Ahmedabad. In this paper we describe the construction of the probe, present the results and compare the findings with what would be expected on the basis of a somewhat simplified but widely used theory of penetration of temperature wave through the layers of soil.

The Probe

A schematic diagram of the probe installed at the campus of Indian Institute of Management, Vastrapur, Ahmedabad in August 1999 is shown in **figure-1**. It consists of a 4-m long, 50-mm diameter PVC tube on which sensors are mounted. Sensors are put through a hole on the tube and protrude outside about 5 mm. Probe has five sensors (RTDs - PT 100). Length of lead wires of all five sensors has been kept equal (3.5 m). The ambient air sensor is shaded to protect it from the direct sun. Sensors are connected to a common digital indicator with a selector switch. The sensors are placed at 3-m, 2-m, 1-m depth below ground. One sensor is placed 1-m above ground. One is placed just 2-cm below the surface. After installation of sensors, tube was filled with granules of thermocole to prevent convective transfer of heat from one level to another. Top end of the tube was closed with tape to prevent entry of water. Bottom end is simply set on the soil, but otherwise open. This was done to let water drain out by gravity in the event it finds its way into the tube. A pit was dug and probe installed. Pit was then backfilled carefully to ensure that sensor tips protruding into the soil are not damaged. All sensors were checked in laboratory for calibration and accuracy before installation.

Temperature Data

Temperatures were noted on hourly basis one day in each month, usually near the middle.

Results

Diurnal Variation

Figure-2 shows the temperatures on August 20-21. The ambient temperature varied from a minimum of 22.7^{o}C to maximum of 31.5^{o}C. The amplitude of fluctuation was thus, 4.4^{o}C. Amplitude is half of the difference between the maximum and the minimum. At 1-m depth the temperature varied from 25.2^{o}C to 25.4^{o}C only. The amplitude was reduced to just 0.35^{o}C. There was also hardly any fluctuation further down at 2-m and 3-m depth. **Table-1** shows the amplitude of diurnal fluctuation on a day in each month in the ambient and in soil at various depths including the surface. It can be seen that the same pattern - reduction in diurnal fluctuation with depth - was uniformly present through twelve months.

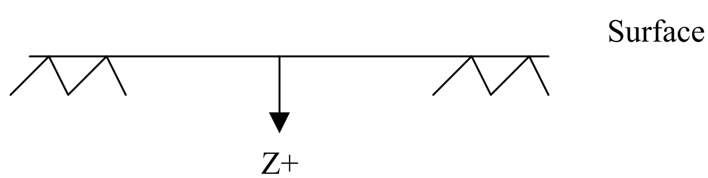
Annual Variation: Damping of Amplitude and Phase Lag with Depth

In order to see the variation through the twelve months, hourly observations of a day were averaged to get the daily mean. Diurnal function is thus removed, leaving only the fluctuations that occur over a longer period. **Table-2** shows the data. **Figure-3** shows the same data graphically. From table-2 (column-3), it can be seen that the maximum temperature on the soil surface during the year was 35.6^{o}C (April) and minimum was 15.5^{o}C (January). The amplitude of annual variation at the soil surface was thus 10^{o}C. At 1-m depth it reduced to 4.6^{o}C, at 2 m to 3.2^{o}C and at 3 m to just 2.8^{o}C. These values were normalised with that at the surface. Normalised amplitudes at 1-m, 2-m and 3-m depth are 0.46, 0.32 and 0.28 respectively. Attenuation of the annual wave is clearly evident, as it penetrates into the soil. It is also seen that the damping of amplitude with depth is less rapid than in case of the diurnal wave.

From **figure-3,** it can also be seen that the peak of annual wave at the soil surface is in early April. As one moves deeper, peak occurs later. At the depth of one meter, it is near the middle of June. At 2-m and 3-m it shifts further to the right. July and August are the usual rainy months in Ahmedabad. It is because of this that the temperature lines sometimes intercept each other. But phase-lag associated with depth is visible.

Analytical Expression for Daily Mean Soil Temperature at Ahmedabad

Consider a semi-infinite medium as shown below. Consider further that the entire medium is initially at a known constant temperature. Surface of the medium is maintained at a temperature that varies harmonically.



Let

Z	space coordinate (here depth below surface, positive downward) m
t	time (days)
$T_{(z,t)}$	temperature of points at depth z, time t (^{o}C)

T_a	temperature of the medium initially (^oC), constant
A_0	amplitude of the temperature wave at the surface (^oC)
ω	angular frequency of the temperature wave at the surface (rad/day)
k	thermal diffusivity of the material of which the medium is made (m^2/day)

Equation (1) describes one dimensional heat flow through the semi-infinite (z>0) medium

$$\frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial Z^2} = 0 \quad \ldots\ldots \quad (1)$$

Initial Condition (at t = 0)

$$T_{(z,0)} = T_a \quad \ldots\ldots. \quad (2)$$

Boundary condition (at z = 0 , t > 0)

$$T_{(0,\,t)} = T_a + A_o \cos(\omega t - \varepsilon) \quad \ldots\ldots \quad (3)$$

ε parameter to indicate the time origin

By a change of variable, initial and boundary conditions can be made simpler.

Let

$$\theta = T - T_a$$

Equation (1), initial condition (2), and boundary condition (3) can now be written as

$$\frac{\partial \theta}{\partial t} - k \frac{\partial^2 \theta}{\partial z^2} = 0 \quad \ldots\ldots. \quad (4)$$

$$\theta(z, 0) = 0 \quad \ldots\ldots.. \quad (5)$$

$$\theta(0, t) = A_0 \cos(\omega t - \varepsilon) \quad \ldots. \quad (6)$$

The steady state solution of (4), which satisfies (5) and (6), can be found in many texts **[5,6]** and is

$$\theta (z, t) = A_0 e^{-\propto z} \cos (\omega t - \propto z - \varepsilon) \quad . . . . (7)$$

where

$$\alpha = \sqrt{\frac{\omega}{2k}}$$

In terms of original variable T (z, t),

$$T (z, t) = T_a + A_0 e^{-\propto z} \cos (\omega t - \propto z - \varepsilon) \quad . . . (8)$$

Equation (8) represents a temperature wave of wave number, $\propto$. Amplitude of fluctuations reduce as the wave penetrates into the medium, by a factor

$$e^{-\alpha z} \quad or \quad e^{-\sqrt{\frac{\omega}{2k}} z}$$

Thus, the waves are very strongly attenuated, especially the higher harmonics. In other words, diurnal waves will dampen more rapidly than the annual. Lower the thermal diffusivity, more rapid the attenuation. This formulation is widely used to study the soil temperature regime. Yet, it is appropriate to bear in mind that it is a simplified view of otherwise more complex situation. Soil temperature is dependent on convective, latent and radiative heat exchange between soil and atmosphere. All this is not accounted for. Effect of occasional rains is ignored. Soil is assumed to be homogeneous, which often is not the case. Moisture regime varies in soil with depth, which will change the thermophysical properties assumed constant here. Nevertheless, as we will see presently the main effects are well captured by the above formulation.

Soil Temperature Regime at Ahmedabad

In order to make equation (8) specific to Ahmedabad, we need to determine T_a, A_0, and $\in$ from empirical data. Although an approximate magnitude of average soil temperature could be derived from our data, it would not be satisfactory, being based on only one-year data. Average soil temperature is expected to be equal to the (long-term) annual mean air temperature. Mean air temperature for Ahmedabad based on ten-year data, is published in ***Handbook of Solar Radiation Data of India*** **[7]**. The mean is 27^oC. We will use this as an approximation of the average soil temperature (T_a).

Amplitude A_0 of the annual temperature wave at the soil surface is 10^oC (**table-2, column-3**). Value of $\in$ can be determined by noting (**figure-3**) that the peak of the wave at the surface occurs at about the day 105 (April 15). Using these values soil temperature regime at Ahmedabad can be described by,

$$T(t,z) \; = \; 27 + 10 \quad e^{-\alpha z} \; \cos \left[\frac{2\pi}{365} (t-105) - \alpha z \right] \qquad ....(9)$$

Parameter, $\propto$ relates to the thermophysical property of soil. Probe is installed on a lawn, which has some shrubbery nearby. Soil samples were drawn from three locations as the pit was dug and tested at Soil Mechanics Laboratory of L.D. Engineering College, Ahmedabad. Test results given below indicated that the soil is silt loam.

Soil Sample depth	:	1.5 m
Field moisture content:		15.74 (% d.b)
Grain size analysis	:	Sand - 48%, Silt - 41%, Clay - 11%,

The Lab is not equipped to measure thermal diffusivity. Values for a set of materials including soils of various types (both wet and dry) are tabulated in **[5, 6]**. We will use the values for wet and dry loam drawn from these sources.

Amplitude Attenuation and Phase Lag : Measured and Predicted

Attenuation

Figure-4 shows the waves at the surface, 1-m, 2-m and 3-m depth using equation (9) with thermal diffusivity of wet loam. Note the amplitude of the wave at surface is 10^{o}C. We, of course, have set this. The amplitudes get attenuated with depth. At 1-m depth it is reduced to 6.7^{o}C, at 2-m to 4.4^{o}C and at 3-m, 2.9^{o}C. Normalized magnitudes of these are listed in **table-3** for comparison with the ones resulting from our measurements. Table also lists the computed values for dry loam. Note that the measured values lie between the wet and dry loam values. Accordingly, these can be considered reasonable.

Phase Lag

Figure-4 clearly shows the increase in phase lag with depth. Occurrence of peaks is delayed at deeper layers. The peak of the wave at 1-m depth for instance occurs about 24 days later than that of the wave at surface, which occurs near about April 15. At 2-m depth the delay increases to 48 days and at 3-m depth to 72 days. Delay in occurrence of peaks is evident in the measured values as well (**figure-3**), though it is difficult to tell clearly the magnitude of delay. Occurrence of rains in late June, July and August cools the surface tending to flatten the peaks. Presently we will conclude only that the attenuation and phase lags predicted by equation (9) are broadly supported by the empirical results.

Conclusion

1. Measurement of temperature upto the depth of 3-m at Ahmedabad displays the pattern known to exist elsewhere. Diurnal fluctuations diminish rapidly with depth, such that the temperatures at 1-m and beyond become constant except for seasonal changes. Amplitudes of annual wave too diminish with depth, but less rapidly than the diurnal.

2. Temperature at 1-m depth varies from a low of 21^{o}C in January to a high of 30^{o}C in June. At 2-m depth the variation in between 22^{o}C - 28.4^{o}C. At 3-m depth it is between 24^{o}C and 29.8^{o}C. The strata between 2-m to 3-m appears well suited for siting of earth tube heat exchanger. Amplitudes will of course diminish further if one went deeper. But then, the cost of trenching will increase without significant reduction in amplitude.

Table-1 Amplitudes of Diurnal Temperature Fluctuation (^{o}C)					
Day	**+1 m (ambient)**	**0 (soil surface)**	**-1 m**	**-2 m**	**-3 m**
January 15	8.7	5.45	0	0	0
February 15	8.5	7.8	0	0	0
March 15	10.5	12.5	0	0	0
April 15	10.1	14.85	0	0	0
May 15	6.9	11.95	0	0	0
June 20	6.4	8.65	0.1	0	0
July 20	6.95	8.2	0	0	0
August 20	4.4	5.5	0.35	0.15	0.3
September 15	3.4	2.3	0	0	0.05
October 11	5.5	3.1	0	0.05	0.05
November 16	5.9	3.9	0	0.05	0
December 13	65	5.6	0	0.05	0

Table-2

Ambient and Soil Temperature on a typical day of each month at the Campus of Indian Institute of Management, Ahmedabad

Month	Ambient (^{0}C)	Soil Temperature (^{0}C) at Depth			
Date	1 m	0 m (Soil Surface)	-1 m	-2 m	-3 m
January 15	20.0	15.5	20.9	22.5	24.2
February 15	23.1	17.1	20.9	22.0	25.2
March 15	27.4	26.4	22.5	22.3	25.8
April 15	31.6	35.6	25.8	23.8	26.6
May 15	33.8	34.8	28.8	26.4	26.6
June 20	31.8	34.8	30.2	28.1	29.8
July 20	28.7	31.9	30	28.4	28.5
August 20	28.0	26.3	25.6	26.3	28.9
September 15	28.0	27.5	26.5	26.6	25.6
October 11	27.7	27.6	26.0	26.7	26.1
November 16	24.3	24.5	23.9	25.2	24.3
December 13	21.0	20.1	22.2	24.0	24.4
Amplitude	**6.9**	**10.0**	**4.6**	**3.2**	**2.8**

Note : Values are mean of 24 hours.

Table-3
Amplitude Attenuation

Depth (m)	**Amplitude Measured (*normalised*)**	**Normalised Amplitude Computed (*wet loam*)**	**Normalised Amplitude Computed (*dry loam*)**
0	1	1	1
1	0.45	0.67	0.48
2	0.31	0.44	0.23
3	0.27	0.29	0.11

Note : Thermal diffusivity (k) for wet loam was taken to be 0.0518 m^2/day, for dry loam 0.0155 m^2/day)

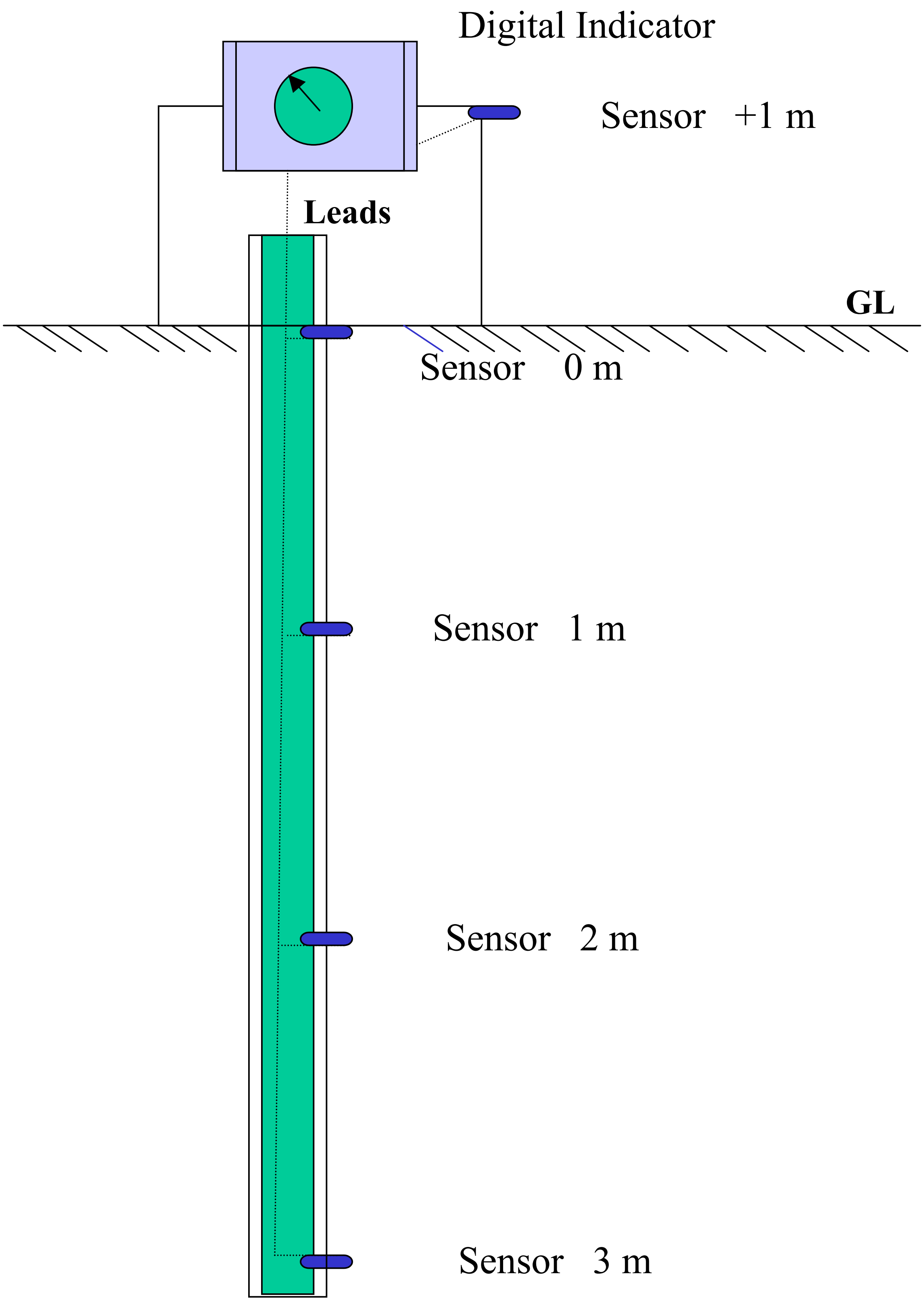


Figure-1: Temperature Probe at IIM Ahmedabad Campus

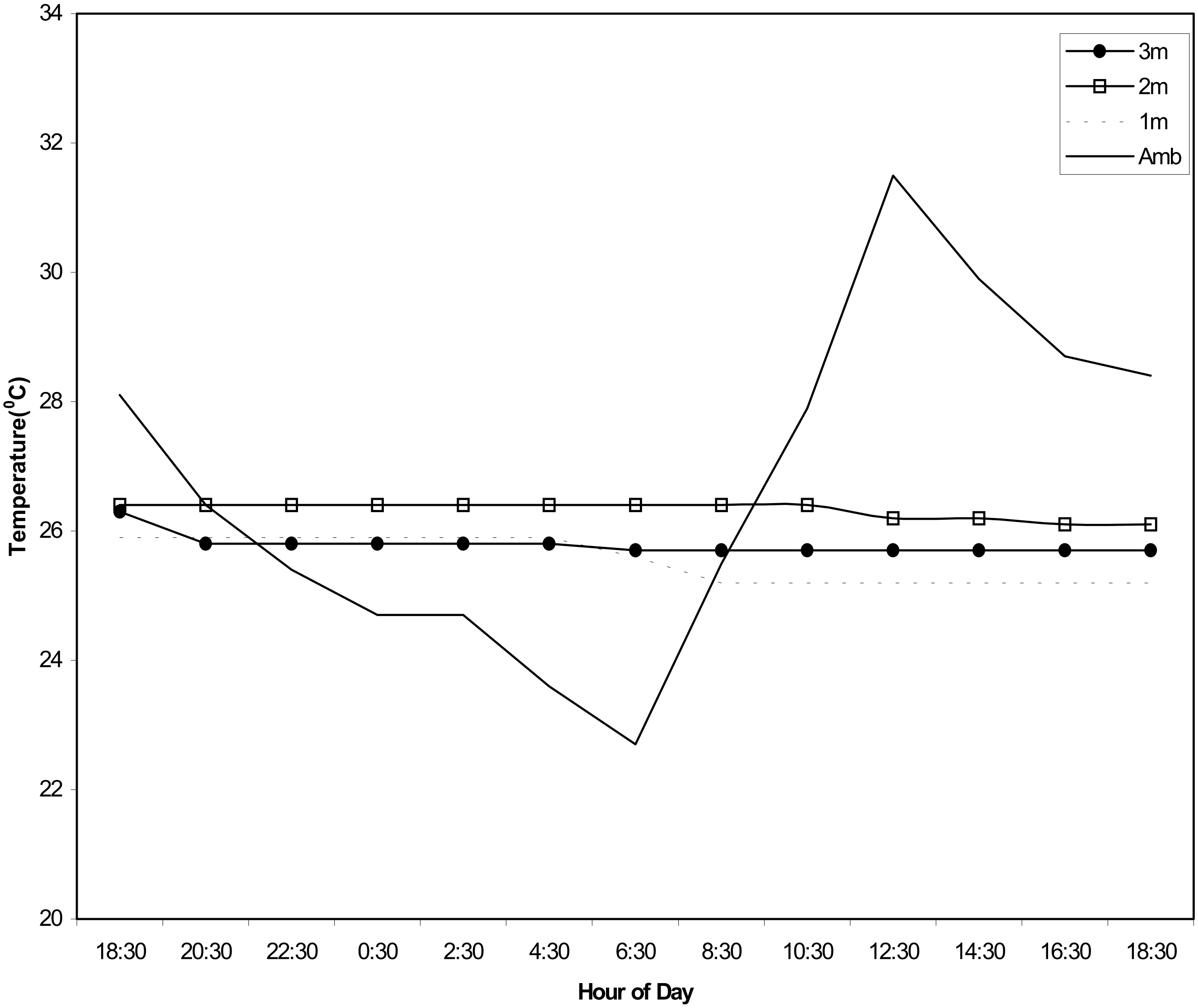


Figure-2: Soil Temperature at various depth and ambient air at IIM campus Ahmedabad *20 - 21 August 1999*

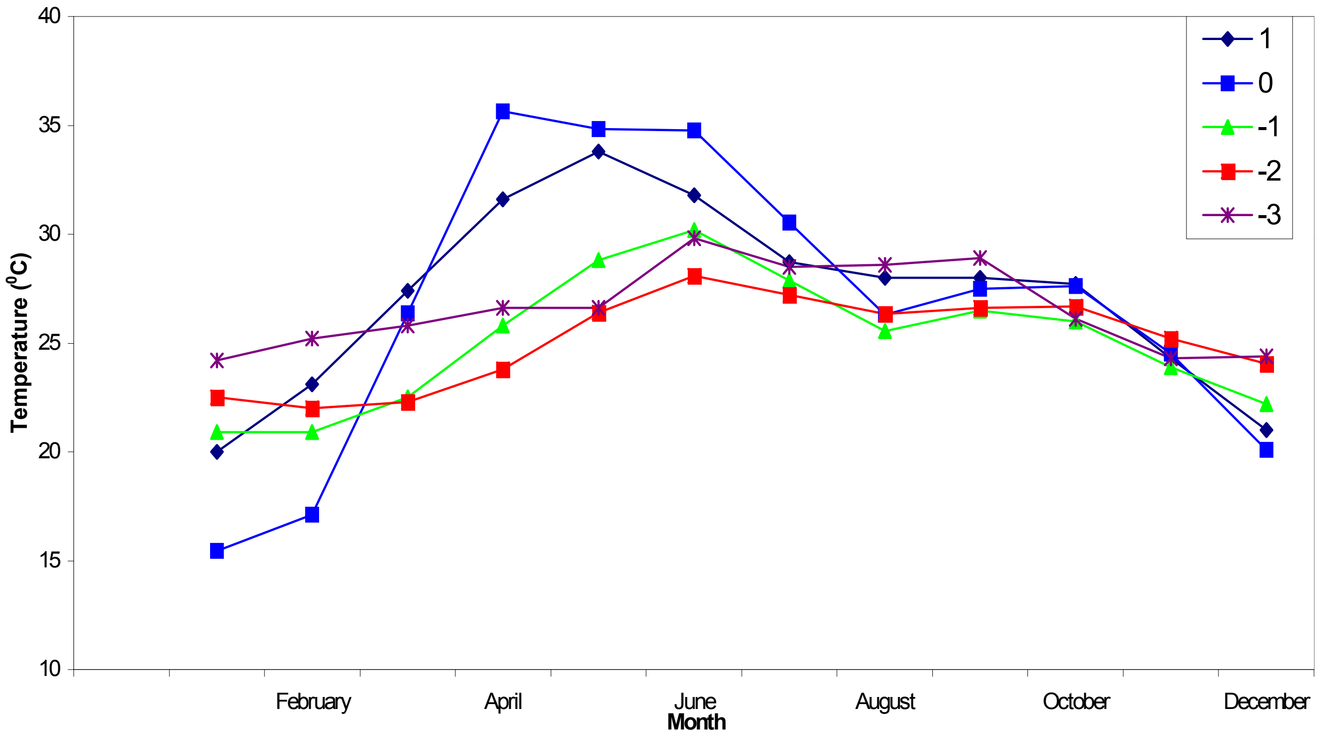
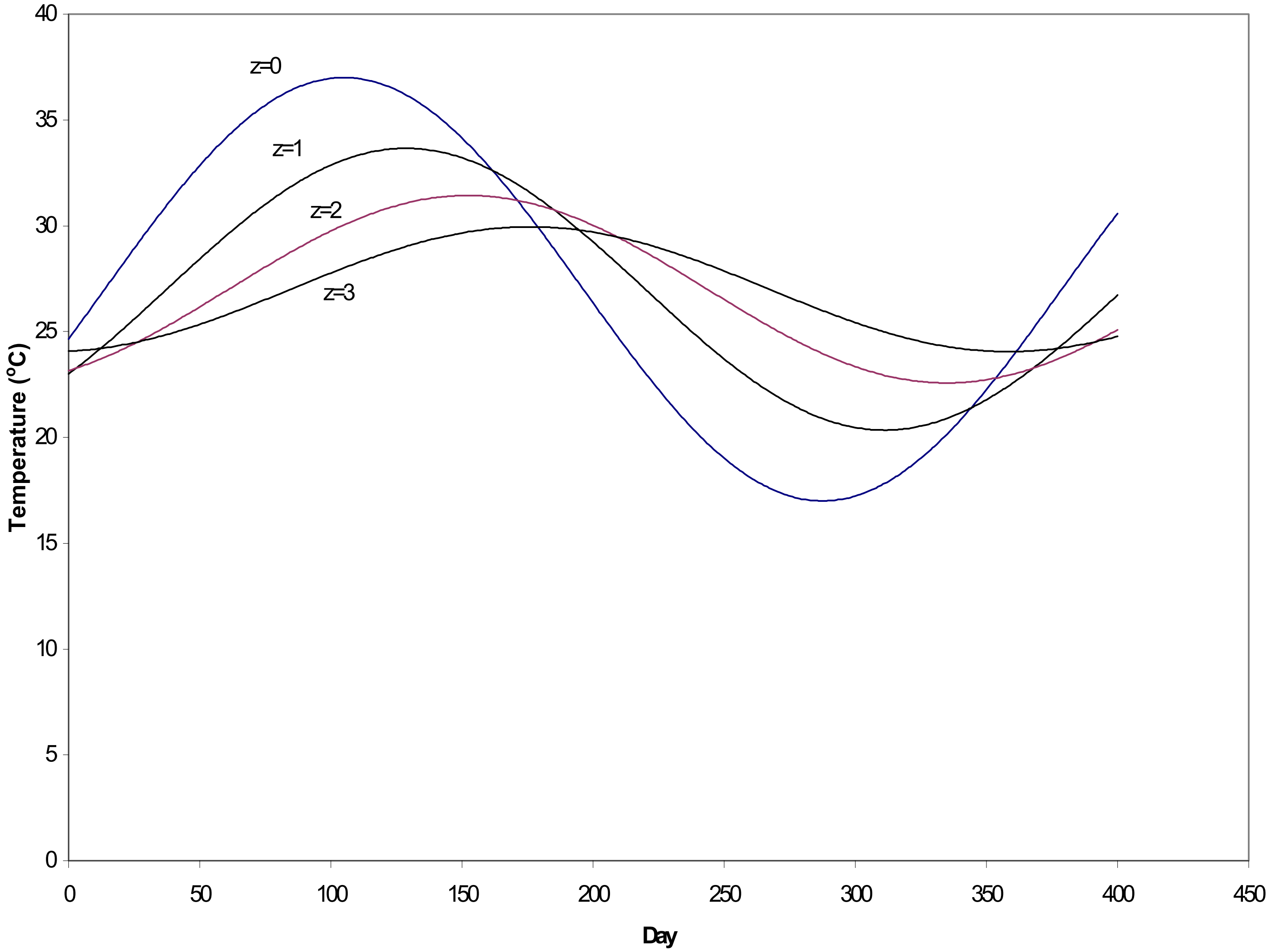


Figure-3: Ambient and Soil temperature at the Campus of IIM Ahmedabad

Figure-4: Simulated Soil Temperature Regime at Ahmedabad



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