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A numerical and field investigation of underground temperatures under Urban Heat Island

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ABSTRACT

This paper introduces a simplified model for underground temperature prediction in summer hot weather. The data of 14 observation sites show that the surface temperature curves are close to trapeziums, and surface temperatures are related to air temperatures. Therefore, approximated temperature trapeziums that are determined by high- and lowest air temperatures can be used to simulate the underground temperature variation. Two observation sites respectively in the urban and suburban areas were used as examples. Good agreement was obtained between simulated- and measured temperatures. Measured data indicate the average temperature under urban concrete surface is 3.70 °C greater than that of suburban bare surface. The deviation is due to the heat urban environment effect and different surfaces effect, which are about 1.68 °C and 2.02 °C, respectively. Combined with soil volumetric water content (w_v), 'Heat' Islands associates with 'Dry' Islands, which means urban soil moisture is lower than suburban soil moisture (13.9%). According to the variation of w_v and temperature deviation graphs, Urban Heat Island, ground surface types and rainfall are important factors that influence the underground soil moisture and temperatures.

1. Introduction

In an age of urbanization and global warming, the influence of Urban Heat Island (UHI) is more and more significant [10,19]. Temperature variation impacts on the engineering properties of urban soils, and consequently changes the strength and stability of various engineered structures. Many previous studies show that the increase of shallow soil temperature influences soil permeability, suction of unsaturated soils, and soils shear strength etc [11,24]. Underground temperature prediction therefore plays an important role in the research of issues related to environment, energy sources and engineering [7,16,22].

The causes of UHI are not the same in different climates or city features. Therefore, many models and approaches, including observation and simulation techniques, have been proposed to understand the causes of UHI formation and to mitigate the corresponding effects [9,15,26]. Santamouris [21] reviewed observational studies of UHI for European cities. Mirzaei [15] presented a review of the techniques used to study UHI, and discussed the abilities and limitations of each approach for the investigation of UHI mitigation and prediction. Huang et al. [9] investigated the diurnal changes of urban and rural air temperatures in four types of ground cover and Urban Heat Island of Nanjing. Their study indicates that the Urban Heat Island Intensity varies in time and on different surface types. However, surface temperatures, underground temperatures, and corresponding UHI effect are not involved.

Continuous monitoring of underground temperature is expensive. Analytical methods and computer technologies can provide cheaper, alternative ways to predict the underground temperatures. However, the underground temperature field is influenced by many factors, including solar radiation, air temperature, wind speed, rainfall, shelter, and soil properties [5,14]. Most of these factors change irregularly and as a result, the prediction and estimation of underground temperature is complex. In previous studies, many analytical models [23], semi-analytical models [6,27], empirical models [1,2], numerical methods [12,18], Fourier models [8] and neural network methods [3] have been used to solve various heat transfer problems [17]. Most of these methods require many measured parameters, some of which are hard to obtain under real field conditions.

On the basis of the relationship between air temperatures and surface temperatures, a simplified model is introduced to simulate the variation of underground soil temperatures during summer hot weather. The method has been used to estimate the underground

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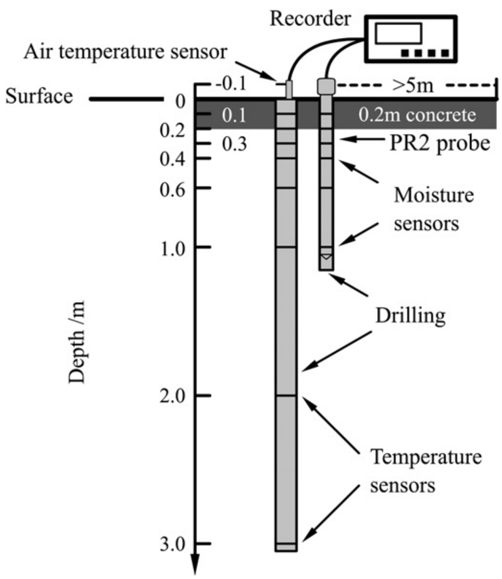

Fig. 1. Temperature and moisture monitoring diagram.

temperatures of concrete and bare soil surfaces in two sites of Nanjing (China). The simulated temperatures are compared with the measured data to investigate the influence factors of the Urban Heat Island. Combined with the field moisture data, the influences of UHI, surface types and rainfall infiltration on the underground temperatures and moisture are analyzed.

2. Field temperature survey

Nanjing (East China, 32.04°N, 118.78°E) is the capital of Jiangsu province and situated in one of the largest economic zones of China, the Yangtze River Delta. The city's total land area is 6598 square kilometers and the urban population is over 7 million. Seasons are distinct in Nanjing, with usually hot summers and plenty of rainfall throughout the year.

The main purpose of the field survey is to detect the diurnal variation of air temperatures and surface temperatures with concrete surface and bare soil surface, so as to get the relationship between them. On the basis of the relationship, the daily surface temperatures can be approximated by the air temperatures at 14:00 h and daily lowest air temperatures. These data and the relationship are used to determine the top boundary temperatures in numerical simulation. Meanwhile, the air temperatures, surface temperatures, underground temperatures and moisture of two sites were recorded everyday during the study period in order to compare with simulation results.

2.1. Diurnal surface temperature survey

14 observation sites were installed in the urban area, suburbs and around Xuanwu Lake of Nanjing. The sites are located on open ground without any shelter, such as squares. An air temperature sensor was fixed on a pole at 0.1 m above the ground (air temperature sensor in Fig. 1). Although the air sensor is close to the ground surface, the measured air temperature is still influenced by wind speed. As a result, the wind speed should be less than 4 m/s, when measuring the air temperature. And surface temperature sensors were attached to the ground surface. Then, the temperatures of the concrete surface and bare soil surface were recorded simultaneously at the 14 sites. The concrete surface temperatures, soil surface temperatures and air temperatures of a suburban site are plotted in Fig. 2a. As shown in the figure, temperatures start to rise at 5:00 h; increase quickly in the following 7 h; and peak between 12:00–14:00 h, which is called the high temperature period. Temperatures then decline gradually, bottoming at the low temperature period ranging from 3:00 to 5:00 h of the next day. Therefore, the diurnal surface temperature curves can be approximated by temperature trapeziums (Fig. 2a), which are defined by the highest- and lowest surface temperatures.

Surface temperatures can be calculated from air temperatures on the basis of the relationship between them [14]. According to the diurnal temperature data of the 14 observation sites, surface temperatures and air temperatures are correlated significantly at night, such as in Fig. 2a. Generally, bare soil surface temperatures are 1–2 °C greater than air temperatures during low temperature period. However, the surface temperature fluctuates dramatically at noon, in particular, between 12:00 and 14:00 h. As shown in Table 1, the difference between air temperatures and surface temperatures is greater on dry days (7.7 °C, concrete surface) and lower on rainy days (4.0 °C). Therefore, average temperatures should be used to determine the relationship between air temperatures and surface temperatures.

As shown in Fig. 2b, the temperature trapeziums can be defined by maximum- and minimum surface temperatures, which are determined by air temperatures. And the relationship is expressed as follows:

$$\mu_1(t) = F(AT_{\max} + dT_{\max}, AT_{\min} + dT_{\min}, t) \tag{1}$$

where $AT_{\max}$ is the high air temperature at 14:00 h, $AT_{\min}$ is the daily lowest air temperature; $dT_{\max}$ and $dT_{\min}$ are the corresponding

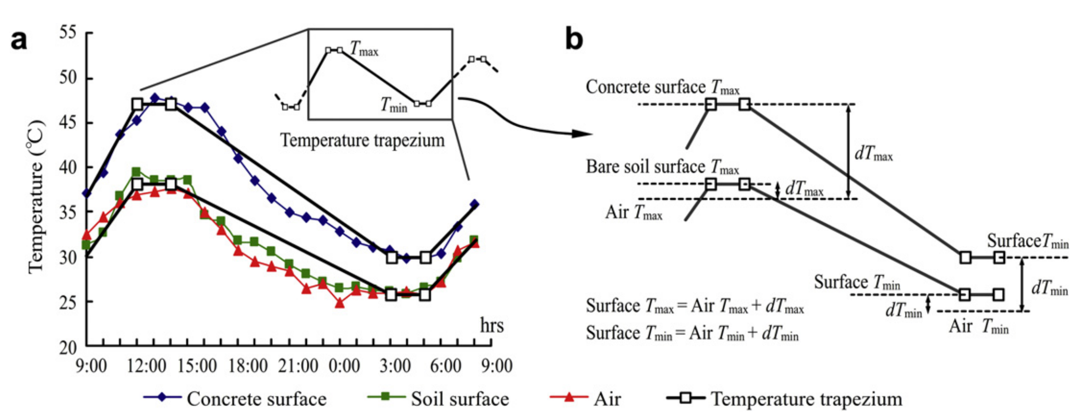

Fig. 2. (a) Diurnal temperatures can be approximated by temperature trapezium, which is defined by maximum- ($T_{\max}$) and minimum surface temperatures ($T_{\min}$). (b) Maximum- and minimum surface temperatures can be calculated from the air temperatures, according to the relationship between them.