The analysis of the causes of underground warming using numerical simulation

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ABSTRACT

The underground thermal environment shows a complex structure that is affected by the topography, geological features, flow of underground water, rise in temperature from urbanization and the landcover composition that composes the underground. However, recently, an energy conservation method that uses thermal heat is gaining attention and there is a need to understand the thermal environment in more detail.

This study measured the ground temperature of gauge wells in the center of Hadano City, Kanagawa. In general, thermal temperature remains constant all year round at a certain depth from the ground surface. But, actual measurement results showed that the closer to the ground surface, the annual temperature rose more. This is thought to be the result of the rising temperature in the city center having an effect on the underground as well. As such, this study, for the purpose of analyzing the causes of underground warming, calculated the underground temperature through numerical simulation and reviewed how changes in the landcover composition structure that forms the ground surface and the temperature rise from urbanization affect underground temperature.

KEYWORDS

Underground warming, Numerical simulation, Underground thermal, Underground water, GIS

INTRODUCTION

Underground thermal environment is complicated as it is affected by topography, geological condition and urbanization-led temperature increase, surface composition change, underground water flow, etc. Recently, underground heat-based energy-saving technology has received increasing attention. Detailed understanding of the underground thermal environment has grown more important to build future responses to the heat island. In this situation, this research, for the purpose of detailed understanding of underground thermal environment, measured the underground temperatures of observatory wells buried in the central part of Hadado City in Kanagawa. Underground temperature, in general, is maintained constant throughout years once it reached a certain level of depth. However, the actual measurement in this study has found that the shallower the depth, the higher the temperature moved.
(underground warming). It seems that this is because of the urbanization. This study, for the purpose of analyzing the causes of underground warming, calculated the underground temperature based on the numerical simulation and examined the effects on underground temperature of urbanization-led temperature rise and landcover composition change.

**STUDY OF THE REGION AND METHOD**

The measurement was performed on the observation wells in the center of Hadano City (2.6kmX2.6km). Hadano City, as it has experienced an underground water pollution accident, has 124 observation wells buried in each 87 points. Of them, 34 wells were chosen for this research temperature measurement. The measurement method is as follows:

**Underground Temperature Measurement**

The depth of each observation wells ranges 8m-74m underground. The measurement was done for 5 times in total to assess underground water level and underground temperature distribution. In 2012 and 2013, the temperature was measured at intervals of 2m and in 2014 at 10cm intervals for more specific understanding (Figure 1. / Table 1.).

**Measurement Results / Discussion**

In general, near surface, underground temperatures change due to the effect of temperature. But once the depth reaches a certain level, the temperature throughout the year tends to stay constant. The temperature in this section is normally 1〜2°C higher than the average temperature of the region so it is called a constant-temperature zone. The 34 observation wells measured herein are grouped into 3 large types.

A type – General underground temperature profile is seen. Of the 34 wells, 15 exhibited this phenomenon. The average depth of constant-temperature zone is GL.-20m and its average underground temperature is 16.92°C which is 2.02°C higher than the average temperature of Hadano City (Figure 2). Also the closer to the surface, the higher the temperature moved in all of the 15 wells constant-temperature zones. This is called a temperature inversion phenomenon. It seems that this is related to the thermal island effect accompanied by urbanization.
B type – Unlike general underground temperature profile, their underground temperature profile is irregular. It seems that this is because of artificial activities in the surrounding areas. Of the 34 wells, 11 showed this phenomenon. They tended to be near factories, schools and buildings or sewerage systems.

C type – Their depth is 20m or shorter. Measuring temperature in any deeper level than that is impossible in this type. Of the 34 wells, 8 fell under this category.

Selection of Observation Well for This Research based on Numerical Simulation
To analyze the causes of underground warming, wells were selected to reproduce the measured underground temperature profiles through the numerical simulation. One well in A type was selected as it showed normal temperature profile without any abnormality in terms of precision, actual depth of measurement, waste heat toward ground (Observation well No. 25). The point subject to calculation is shown in Figure 1.

SUMMARY OF NUMERICAL SIMULATION
Generally, underground temperature changes according to season by the effect of outside air whereas the deep-seated part maintains constant temperature regardless of seasons or depth. But the temperature starts to rise in even deeper levels. The underground temperature distribution observed in the wells of Hadano City, on the other hand, showed temperature inversion that the deeper the level, the lower the temperature (Type A features / Figure 2.). A reason for this seems to be the accumulation of rising underground temperature due to urbanization-led temperature rise and surface changes. Therefore, this research seeks to identify underground temperature distribution through the numerical simulation and the effects of temperature increase which is deemed to be a reason for underground warming or the effects of landcover changes on underground temperature. The model outlook is described hereunder.

Heat and Moisture Transfer and Airflow at Air-Plant-Soil-Continuous Model
The heat-water-air combined movement model is a mathematical one based on the air-planting-soil coupled system used for the numerical simulation of underground temperature distribution. It uses P-model (nonequilibrium thermodynamics model). It
is characterized to describe the whole system as a thermodynamical system unifying in the identical dimension. P-model is a nonequilibrium thermodynamics model formed from energy and moist conservation. It uses thermodynamic energy (moist potential) in consideration of the effect of stress in addition to the impetus of moisture flow as well as the fact that transpiration varies according to the own functional status of soil and planting. That is, more practical phenomena-based electro-thermal analysis becomes possible. Also by dividing plant community in multi-layers virtually, solar heat acquisition in each layer, inter-layer long wave radiation exchange, ventilation, thermal/moist transfer, etc. are considered to reproduce the effects on underground to a detailed extent.

**Heat and Moisture Transfer in Soil Layer and Plant Layer**

In the soil layer, absorption moisture transfer and heat/moist transfer are occurred by roots around the border with the planting layer. Under the assumption that plant root and soil layer have the same temperature, root heat balance is integrated into the soil layer.

- **Heat balance**

\[
\frac{\partial c_p \rho v T}{\partial t} + (c_j, j) \nabla T_s = \nabla \lambda \nabla T_s + \frac{\partial}{\partial t} \nabla \lambda'_{g,s} \nabla \mu_{w,s} \quad (1)
\]

\[
j_i = -\lambda'_{g,s} \nabla \mu_s \quad (2)
\]

- **Moisture balance**

\[
\rho_i \frac{\partial \phi_i}{\partial t} \left( \frac{\partial \mu_s}{\partial t} - \nabla \lambda'_{g,s} \nabla \mu_{w,s} + \nabla \lambda'_{w,s} \nabla \mu_s + \omega_{v,r} \right) \quad (3)
\]

- **Boundary condition**

\[
-\lambda_{g,s} \frac{\partial T}{\partial n} - r_v \lambda_{w,s} \frac{\partial \mu_{w,s}}{\partial n} = \alpha_{c,s} (T_c - T_s) + r_v \lambda_{w,s} \alpha'_{\mu,s} \left( \mu_{w,c} - \mu_{w,s} \right) + \varphi_{SR,s} + \varphi_{LR,s} \quad (4)
\]

\[
-\lambda'_{g,s} \frac{\partial \mu_{w,s}}{\partial n} - \lambda'_{w,s} \frac{\partial \mu_s}{\partial n} = \alpha'_{\mu,s} \left( \mu_{w,c} - \mu_{w,s} \right) + \varphi_{pr} \quad (5)
\]

- **Convective moisture transfer coefficient regarding unsaturated moisture water slope[kg/(m²·s·J/kg)]**

- **Unsaturated water potential[J/kg]**

- **Water potential[J/kg]**

- **Water content[m³/m³]**

- **Radiation heat flux rate[W/m²]**

- **Water-consumption by rainfull and so on[kg/(m²·s)]**

- **Moisture capacity[m³/(m³·J/kg)]**

- **Water absorption flow rate of roots[kg/(m³·s)]**

Concerning stems and leaves, each plant canopy layer is combined to regard as one particle. Regarding heat balance, heat/moist delivery (reducer, latent heat transfer) is considered together with moist calorie caused by long/short waves. Concerning
canopy air heat balance, convection heat delivery with leaf side as well as advection of outside air and inside plant canopy are considered. On the other hand, as for moist transfer, absorption moist from soil, moist transfer to upper roots and stems, moist transfer from leaves to canopy air are considered for plant roots. Concerning canopy air, moist transfer from leaves, outside air and advection inside canopy are considered. But in the uppermost layer plant canopy, outside air is transferred to leaf top, while canopy air and heat • moist are transferred to lower leaf. Also, outside air and heat • moist are considered according to the intra-plant canopy-layer advection.

**Long-Wavelength Radiation Heat Receiving in Plant Layer**

Regarding the effective radiation penetration of each virtually hypofractionated plant canopy, long-wave radiation and attenuation coefficient changing according to the plant leaf direction are considered. Considering the long-wavelength radiation heat received by canopy layer plant. Plant canopy formed from upper/lower layer and mutual radiation with air are considered.

**A Solar Radiation Heat Absorption in Plant Layer**

The appearance of solar radiation absorption, reflexivity, penetration of each plant canopy was calculated based on the solar radiation multiple reflections/absorption results between plant canopies. The heat amount of solar radiation in each layer was calculated by one outlying value of plant canopy layer multiplied by the solar radiation absorption considering incidence solar radiation and multiple reflections/absorption.

**Heat and Water transfer in Plant Layer**

The intra-canopy air current speed was expressed as exponential law and continuous system, motion equation, and energy equation by using the air current speed of outside air. Leaf and surface heat • moist transfer ratio were calculated by using boundary layer theory and heat transfer and matter transfer analogue through the dimensionless equation. As for convection heat transfer rate, the Nu values of forced convection and natural convection were compared and a larger one was used. Concerning the wind speed during Re value calculation, outdoor wind speed 0.3m above canopy was used. As for the intra-canopy, the mean flow velocity of each virtually hypofractionated canopy was utilized. The amount of plant-canopy moist transfer was expressed as the sum of leaf moist transfer amount and soil moist transfer emission amount. If the moist potential difference is expressed as driving force, plant-leaf appearance moist transfer rate and soil moist transfer rate can be used to calculate the moist transfer amount. But, the leaf moist transfer rate is affected by the moist transfer rate of leaf boundary layer and the moist transfer rate of stoma. The stoma moist transfer rate relies on stoma openness. On the other hand, the moist transfer rate of leaf boundary layer relies on wind speed.
The Effect of the Temperature Rise

First of all, underground temperature before urbanization was reproduced, which is deemed to be a cause of underground warming. Calculation conditions are described in Table 2. Until 50 years ago, urbanization was not existent. Therefore no temperature increase was assumed and surface cover composition was supposed green. In the case, the results of underground temperature calculation are shown in Figure 4. At around 10m-deep point, underground temperature was 16°C, showing an almost constant level.

In this condition temperature increase was assumed to have taken place from 50 years before in performing the calculation until now (for 50 years). As for temperature increase, based on the yearly average temperature data since 1965 observed by Hadano City fire department in Figure 5., a model with the expanded AMEDAS metrological data plus temperature increase adjustment was used. The results of underground temperature calculation affected by temperature increase are displayed in Figure 4. Due to temperature increase, yearly average surface temperature rose by 1.5°C. This is a trend similar to the 50-year-long temperature increase rate. Also, it is found that up to 28m depth, temperature increased to cause inclination in underground temperature.

The Effect of Ground Cover Changing

Temperature increase effects were not enough to reproduce the warming and temperature inclination, etc. at a deep-seated layer shown in underground temperature distribution. In this sense, this research reviewed the effects of changes in surface cover. In this review, the surface cover composition 50 years ago was assumed to change from green to non-green for calculation. In greens, heat • moist transfer is calculated by setting the surface layer as an unsaturated moist zone calculation in order to consider surface-layer transpiration effects. Nongreens were divided into two types. In barren spaces, permeable layer is set and in asphalt, non-permeable layer is

<table>
<thead>
<tr>
<th>Term of calculation</th>
<th>Temperature rise</th>
</tr>
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<tbody>
<tr>
<td>Before urbanization</td>
<td>1940~1960 (For 20years)</td>
</tr>
<tr>
<td>After Urbanization</td>
<td>1960~2010 (For 50years)</td>
</tr>
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Figure 4. Results of underground temperature calculation

Figure 5. Annual average air temperature in Hadano City
set without moist transfer. Also, in all surface layers, deep-seated layers are set as a saturated moist zone. Figure 6. shows surface composition-specific underground temperatures. If green changes into barren space, surface temperature rose by 2.1°C and the temperature inclination in deep-seated layer grew larger. As shown in Figure 7. on yearly added latent heat amounts, it seems because plant transpiration amount controlled green surface temperature increase. Also Figure 8. shows that the yearly added solar radiation absorption according to each surface cover composition has almost no difference between green and barren space. But asphalt and barren space exhibited about 22% difference.

This difference makes asphalt surface temperature rise by about 1.8°C compared with barren space while affecting the deep-seated layer warming.

Moreover, in order to reproduce the present underground temperature distribution, the characteristics of nearby areas of the targeted calculation place need to be reflected. Green and non-green spaces are mixed in such nearby areas. Thus, the 100m-radius area from the target place was divided every 20m. Based on the underground temperature distribution calculated at each point, 3D heat effects were reflected. Figure 9. shows the land use of the corresponding area based on GIS. The building-caused incidence solar radiation saving in non-green zones reflected in the solar radiation absorption calculated by setting building-part solar radiation absorption at 0.0, and other asphalt paper solar radiation absorption at 0.9 and using the area-weighed average values. Figure 10. exhibits the foresaid calculation method-based yearly average underground temperature distribution as well as actually-measured yearly average underground temperature distribution. The two graphs almost coincide with the precision of numerical simulation.

According to these results, urbanization-led temperature increase and surface cover composition change were found to have warmed up underground to cause underground temperature inversion.
CONCLUSIONS

This study, for the purpose of “factor analysis of underground warming”, measured underground temperatures of observation wells buried in Hadano City. To clarify causes of underground warming found during the measurement, the heat • moist • air combined transfer model based on air-plant-soil coupling was used to perform the numerical simulation. Hadano City pre-urbanization underground temperature distribution was reproduced with numerical calculation. And based on the status, this study analyzed the effects on underground temperature of urbanization-led surface composition changes and temperature increase deemed as a factor of underground warming. Also by using the GIS, local characteristics of nearby calculation areas such as surface composition were reflected. The underground temperature distribution and underground warming gained in this process were reproduced and compared with actual measurements to check for the accuracy of numerical simulation. By doing so, underground warming was found to have been largely affected by urbanization-led temperature increase and surface composition changes.

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