Simulating urban-heat-island influenced subsurface temperature distribution considering groundwater flow in Meguro, Tokyo: A trial on 3-D model building

-Abstract-

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Background and Objective

Underground urban heat island (UHI) was observed globally[1,2,3]. One way, the subsurface temperature increase was stated as a disturbance of human activities to the natural thermal state of the underground space[1,4], whose potential negative impact to the environment is worried. On the other hand, some researchers positively insist that the underground UHI can be a potential source of shallow geothermal energy[5,6,7]. This study takes the positive viewpoint that subsurface temperature increase is a hopeful shallow geothermal energy.

For utilization of such shallow geothermal energy, a spatial distribution of subsurface temperature has been considered useful for selecting an installation site of geothermal facilities. Spatial distribution of anthropogenic heat flux into the urban aquifer was simulated in two Germany cities based on temperature data[7], but groundwater flow was not considered. Also, even simulation on subsurface temperature in strata heated by subway tunnels was observed with influence of groundwater flow factor[6], it was in a 2-D model instead of a 3-D one. However, a 3-D model is considered to be a better approximation of the strata than a 2-D schematic model, because it can contain more information of study area than the 2-D one, e.g. elevation. Also, heat is very possibly transferred through advection when groundwater flow appears, which may influence the temperature distribution.

Thus, considering groundwater flow in 3-D model is expected necessary for obtaining a precise subsurface temperature distribution to represent the real. Hence, the objective of this study is to add groundwater flow into the 3-D simulation of UHI-influenced subsurface temperature distribution.

Method

An area near the Ohashi Junction in Meguro Ward was chosen as the study area for 3-D model building (Figure 1), as an extension of a 2-D cross section model in previous study[6] (see Figure 1 for location of the cross section). Principally, shape of the study area was decided by connecting the ridge of local groundwater contour, which means that there is almost no groundwater flows through the border of the study area.

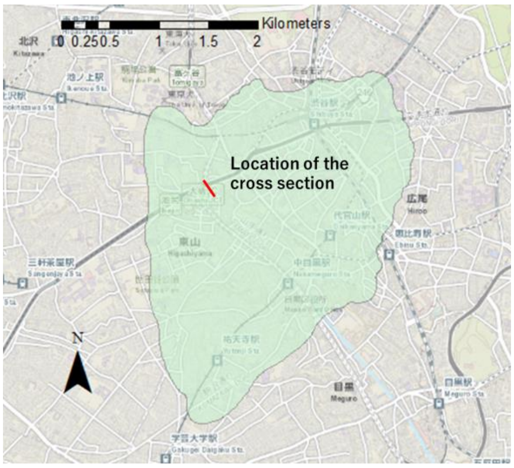


Figure 1 Location of the study area and the 2-D cross section (base map: ESRI map)

Workflow of the simulation in this study and conceptual model for each step is shown in Figure 2. Firstly, a 2-D cross section heated by subway tunnel was built following previous study[6] to obtain a modeling approach, in which the subsurface temperature distribution and groundwater flow can be abstracted conceptually as 2-D rectangle models then as 3-D cubic box models further.

As the second step, extending dimension and capture the UHI-influenced subsurface temperature considering groundwater flow. The groundwater flow mechanisms has been captured as follows: infiltration enters the model domain as potential groundwater recharge, and then the groundwater flow out of the model domain as rivers at places where the land surface elevations suddenly drop, e.g., the river bed. The river water level has been assumed to be relatively stable. The rivers flow downward the landform and finally drain out of the model domain. Fixing the groundwater head result in the model, the natural state of underground thermal environment can be schematically described as average land surface temperature and crustal heat flux heating the strata, which is the initial condition for the model observing the influence of UHI. Start year of the UHI was set as 1945 based on a subsurface temperature measurement[8], from which the land surface temperature has been set to increase. Subsequently, artificial constructions appear in the strata along time line in which they have been opened. Thirdly, to inspect the influence of groundwater flow to subsurface temperature distribution, the calculated contour was replaced by a single head value, preventing groundwater from flowing. These conceptual models were converted into numerical models in FEFLOW simulator in the further step. Geologic layering of the 3-D model was decided by inspecting and comparing a series of geologic cross sections of the study area, after which digital elevation model and elevation data obtained from the geologic cross sections were interpolated into the model. Boundary conditions for each numerical model were listed in Table 1 (T: temperature).

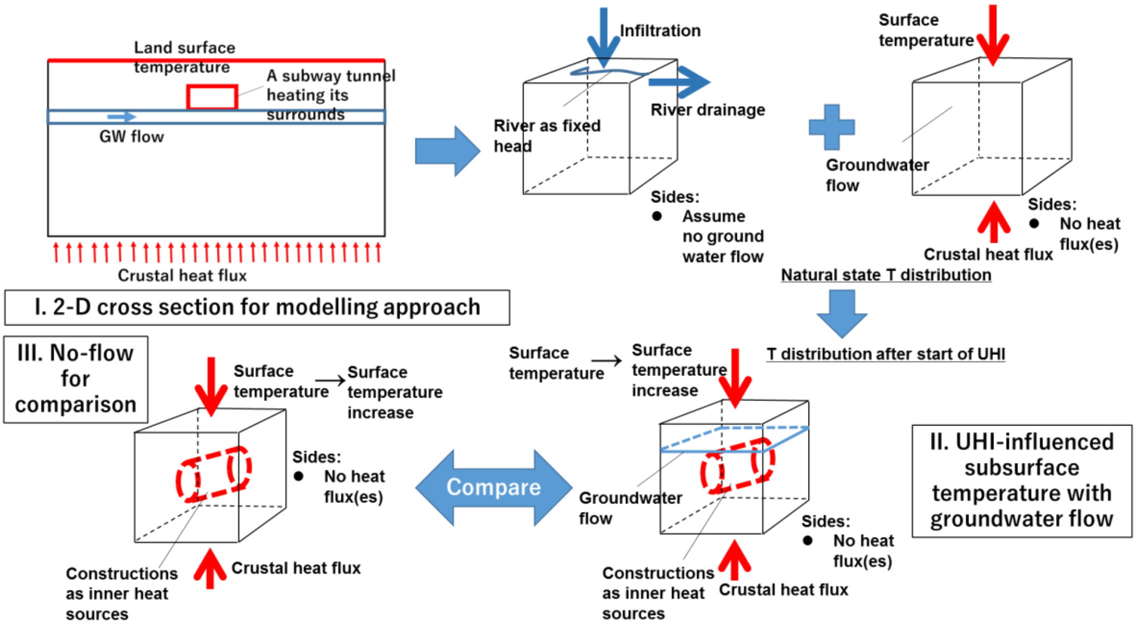


Figure 2 Workflow of the simulation in this study and corresponding conceptual models

Table 1 summary of model boundary conditions

Model Type	**Boundary conditions**				**The initial condition**
	Upper margin	***Lower margin***	***Sides***	***Inside the domain***	
2-D cross section	Increasing land surface T	Literature value of crustal heat flux(Suzuki, 1985)	No heat flow, Darcy flux at aquifer	Yearly changing T of a subway tunnel	T=15+0.15z
3-D natural state subsurface T	Average land surface T		No heat flow,drainage beneath the river	Domain surface: river fixed head	-
3-D T distribution with UHI	Increasing land surface T, land use type specified		No heat flow,drainage beneath the river	Yearly changing T of subway tunnels,average T of the Yamate Tunnel	T=15+0.15z,fixed head distribution

Results and Discussions

To estimate the quality of simulations conducted in this study, the calculated result of the 2-D cross section, the 3-D groundwater flow model and the 3-D UHI-influenced subsurface temperature model combined with groundwater flow were compared to measured data, respectively. Comparisons and corresponding discussions are as follows.

1. The 2-D cross section model

The temperature of calculated profiles are 5 ℃ (T increase given to the UHI-influenced surface boundary condition) higher than the measured near land surface. The with-flow result matched well with the measured at the depth of construction, while no-flow was lower than the measured. The measured geothermal gradient was somehow reproduced (Figure 3). Thus current modeling approach can well reflect the land surface temperature increase caused by UHI, catch the temperature change caused by underground constructions, and somehow reproduce the subsurface temperature gradient of the measured temperature profile.

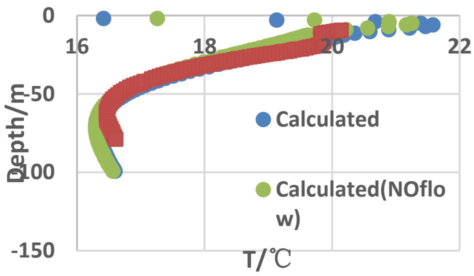
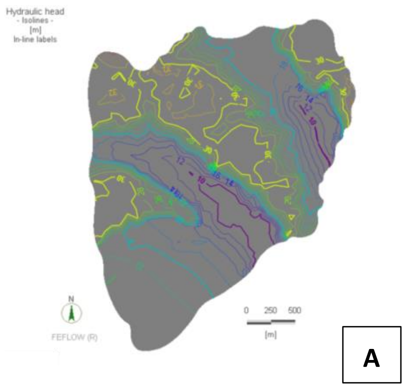


Figure 3 A comparison between the 2-D simulation result and the measured data (source of the measured profile: Fujii, 2010)

2. The 3-D groundwater flow model

Shape of the calculated groundwater contour matched preferably with the measured contour (Figure 4), and the calculated water level at the location where groundwater level was measured has well reproduced the measured value (around 14 m).



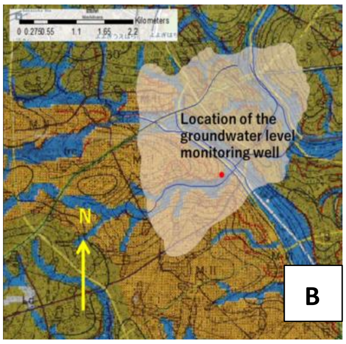


Figure 4 Calculated (A) and measured (B) groundwater contour (source of the base map: Ministry of Land, Infrastructure, Transport and Tourism)

3. The 3-D flow-UHI joint subsurface temperature model

Current model can well catch the influence of groundwater flow to subsurface temperature even further improvement is necessary to facilitate the fitting condition of the results to the measured (Figure 5). Temperature difference caused by groundwater flow can be somehow captured (at depth around -20 m, Figure 5).

Comparing the temperature distribution with and without groundwater flow (Figure 6), it can be found that the flow lowers general level of temperature, but will carry heat downstream, enlarging influence range of the heat sources.

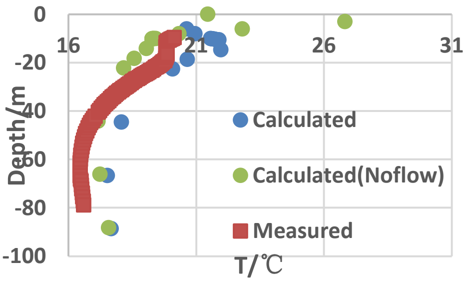


Figure 5 A comparison between the 3-D simulation result and the measured data (source of the measured profile: Fujii, 2010)

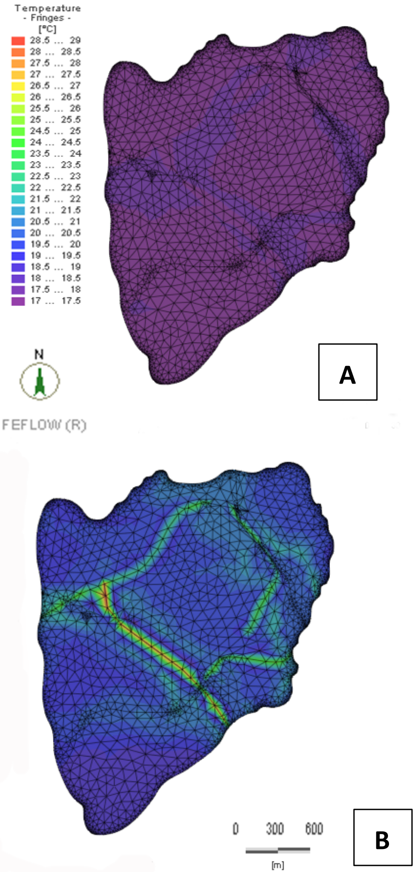


Figure 6 Calculated result of UHI-influenced subsurface temperature distribution (A) with and (B) without the influence of groundwater flow

Conclusions

It has been concluded that (i) current modeling approach is reliable that steady-state simulation can well reproduce the groundwater contour of study area, and the influence of groundwater flow to subsurface temperature can be caught; (ii) groundwater flow do influence subsurface temperature distribution, hence current approach in considered helpful to improve the accuracy of heat stock map of the UHI.

Reference

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