

Peer-reviewed Conference Contribution

Deformations caused by subsurface heat islands: a study on the Chicago Loop

Alessandro F. Rotta Loria^{1,*}¹ Northwestern University, Department of Civil and Environmental Engineering, Mechanics and Energy Laboratory, 2145 Sheridan Road, Evanston, Illinois 60208, United States of America* Corresponding author: af-rottaloria@northwestern.edu

The ground beneath urban areas is warming up due to anthropogenic activity, leading to subsurface urban heat islands [1]. A recent review of the literature suggests that subsurface heat islands are causing an increase in average ground temperature between 0.1 to 2.5°C per decade down to 100 m of depth in various cities across the world [2]. Studies highlight multiple impacts of subsurface temperature rises on urban areas. Subsurface temperature rises can affect the biochemical state [e.g., 3] and hydrogeological state [e.g., 4] of the urban underground, leading to shifts in plant growth and thermal pollution of groundwaters, among other issues. Subsurface temperature rises can also cause transportation infrastructure and public health issues, such as overheated subway rails that force trains to slow down or stop to avoid incidents, and extreme air temperatures underground that cause heat induced diseases [e.g., 5,6]. Meanwhile, subsurface temperature rises represent an opportunity, as geothermal technologies can harness and reutilize additional heat from the ground [e.g., 7,8].

Motivated by the lack of a fundamental understanding of the impacts of subsurface heat islands on the performance of civil infrastructure, this study addresses such knowledge gap and validates its underlying hypothesis with reference to a real case study: the Chicago Loop district – the densest district in the US after Manhattan, which suffers from an urban heat island [2]. Two facilities are used to explore this complex problem: a 3-D computer model of the Chicago Loop and a wireless temperature sensing network installed in surface and subsurface environments across such district.

The developed computer model reproduces the urban morphology of the Loop with due account of the building basements, underground parking garages, subway tunnels, and train stations that characterize such a district. Based on a substantial amount of temperature data gathered from these underground built environments and the ground surface, the model allows for the simulation of the waste heat continuously injected into the ground of the studied area. The employed simulation approach consists of 3-D, time-dependent, thermo-hydro-mechanical finite element modeling, which not only allows to quantify the temperature variations that characterize the subsurface of the Loop in space and time but also their effects on its deformation and the groundwater flow.

Simulations are performed over 100 years: from 1951, when the subway tunnels in the Loop were completed and the morphology of its underground built environments approached the current state, till 2051. The simulation results provide ground temperature values that match with recent data collected from the heart of the Loop's subsurface (Figure 1). On the one hand, this evidence allows retrieving the evolution of the temperature field across Loop from the 1950s to date. On the other hand, this result allows for the prediction of temperature rises that are likely to develop over the next thirty years in the subsurface of the Loop (Figure 2(a)). Jointly, the results provide a first quantification of the thermally induced ground deformations and displacements resulting from subsurface urban heat islands considering the Loop (Figure 2(b)).

This work indicates that temperature variations of several degrees Celsius and thermally induced displacements of several millimeters have affected the subsurface of the Loop over the past 70 years due to waste heat deriving from underground built environments and the ground surface. Vertical ground displacements of the order of millimeters can affect the operational performance of foundations and earth retaining structures, as they can fully mobilize the shaft capacity of piles or induce excessive deflections for

walls and slabs [9]. Therefore, the underground climate change that has affected the Loop over the past 70 years might have silently contributed to the documented operational issues for buildings and infrastructures in such district [10,11], such as excessive settlements of foundations and cracking of structural members. Currently, the ground underneath the Loop is in a thermal quasi-steady state. Accordingly, the obtained results indicate limited average temperature rises and thermally induced displacements for the subsurface in the years to come. However, the ongoing underground climate change should be mitigated to avoid future unwanted impacts on civil structures and infrastructures.

This paper reveals a silent yet threatening impact of subsurface urban heat islands on the operational performance of civil structures and infrastructures (e.g., building foundations, earth-retaining structures, and other underground facilities). The root of this issue lies in thermally induced ground deformations and displacements caused by subsurface urban heat islands, which develop slowly but continuously in the urban underground and can become an issue with time. In this study, a 3-D computer model of a city district, informed and validated by temperature data gathered in the field, has been used to explore the impacts of subsurface heat islands on the performance of civil infrastructures. The results of this work lay the groundwork for future investigations referring to other city districts and specific building foundation types that may be affected by subsurface urban heat islands.

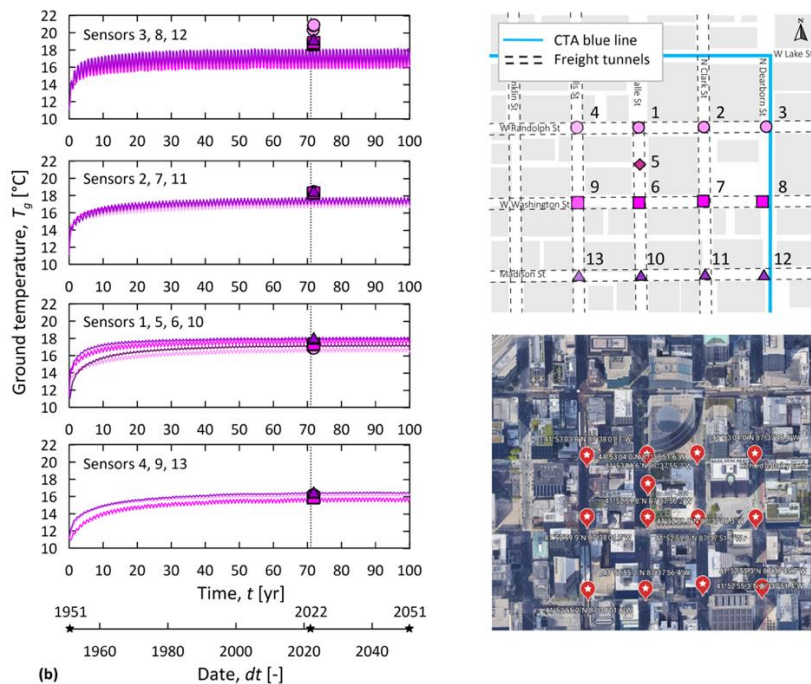


Figure 1: Comparison between the ground temperature evolutions over time t provided by the model in the hearth of the Loop and the sensing network.

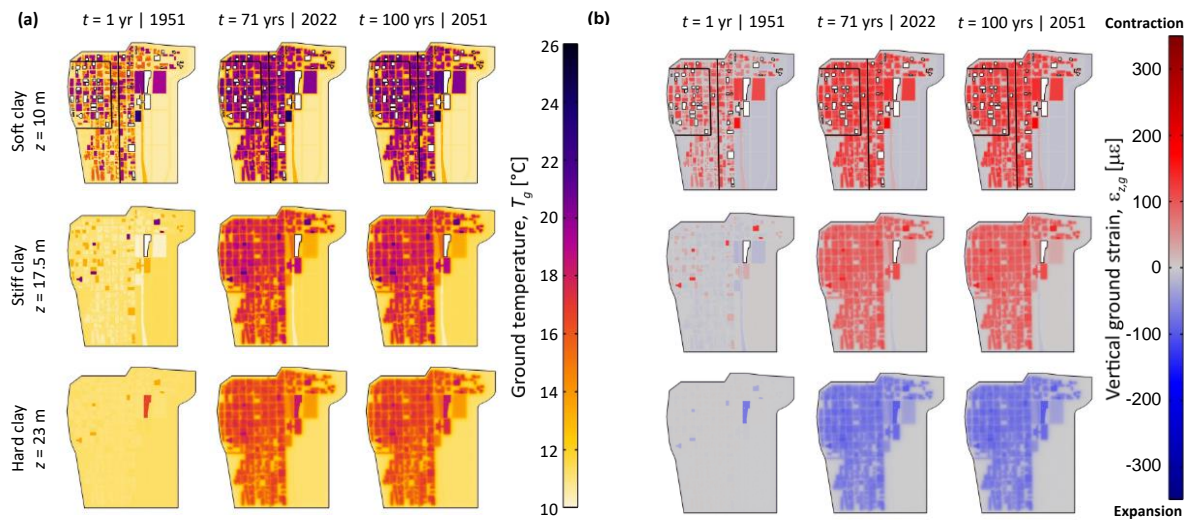


Figure 2: (a) Ground temperature distributions, T_g , at varying depths, z , and times, t ; and (b) Thermally induced vertical strains in the ground, $\epsilon_{z,g}$, at varying depths, z , and times, t .

References

- [1] H.E. Landsberg (1956) The climate of towns, Man's Role Chang. *Face Earth*. 2, 584–606.
- [2] A.F. Rotta Loria, A. Thota, A.M. Thomas, N. Friedle, J.M. Lautenberg, E.C. Song (2022) Subsurface heat island across the Chicago Loop district: analysis of localized drivers, *Urban Clim*. 44, 101211.
- [3] K. Menberg, P. Blum, A. Schaffitel, P. Bayer (2013) Long-term evolution of anthropogenic heat fluxes into a subsurface urban heat island, *Environ. Sci. Technol*. 47, 9747–9755.
- [4] G. Ferguson, A.D. Woodbury (2004) Subsurface heat flow in an urban environment, *J. Geophys. Res. Solid Earth*. 109.
- [5] J. Temperton (2018) *Why is London's Central line so hot? Science has the answer*, WIRED.
- [6] S. Musaddique (2018) *The world's most famous transport system could soon be too hot to ride*, CNBC.
- [7] P. Bayer, G. Attard, P. Blum, K. Menberg (2019) The geothermal potential of cities, *Renew. Sustain. Energy Rev*. 106, 17–30.
- [8] A. Bidarmaghz, R. Choudhary, G. Narsilio, K. Soga (2021) Impacts of underground climate change on urban geothermal potential: Lessons learnt from a case study in London, *Sci. Total Environ*. 778, 146196.
- [9] L. Laloui, A.F. Rotta Loria, (2019) *Analysis and Design of Energy Geostructures*, Academic Press.
- [10] F.A. Randall, F.H. Randall, J.D. Randall (2019) *History of the Development of Building Construction in Chicago*.
- [11] B.G. Moffat (2002) *The Chicago Tunnel Story*, Central Electric Railfans' Association.