



## Working in underground spaces: Architectural parameters, perceptions and thermal comfort measurements



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### ABSTRACT

Rapid economic growth and high urbanization rates create an urgent need for more space in major cities in China. Further development of underground spaces (UGS) is a viable solution that the Chinese government is promoting. For instance, the 13th 5-year Plan for Urban Underground Space Planning suggests that a comprehensive system for UGS planning and management should be established in at least 50% of Chinese cities by 2020. It is thus imperative to better understand how the architectural and engineering aspects of UGS affect human worker's performance, well-being, health, and preferences. The present study reports a comprehensive examination of spaces and occupants of UGS in four major Chinese cities (Beijing, Shanghai, Nanjing and Fuzhou). We investigated thermal comfort conditions in UGS without heating and cooling, and estimated the potential of energy saving during transitional seasons. The results indicate that local climate – and especially the humidity level - is a key factor affecting the thermal behaviour of underground structures. In-depth interviews with workers in UGS indicated that immediate access to above ground greenery, indoor plants, and individual control over the environment compensate for a windowless workspace, and those working in UGS did not perceive to have any sleep disturbances. Previous experience with UGS improved the perception of current underground environments. UGS might even be appreciated as working environments with a good acoustic quality. Overall, the present study challenges the uniformity of standards for the construction of UGS, as it suggests that both climatic conditions as well as user preferences should be taken into account.

## 1. Introduction

### 1.1. Rapid development of urban underground space

Underground space (UGS) is playing an important role in the planning and development of modern urbanization (Delmastro et al., 2016). As an efficient and sustainable infrastructure, UGS shows great economic advantage in coping with dense populations in cities and the high demand for space and mobility (Admiraal and Cornaro, 2016). The demand-driven planning of UGS is common in many major cities worldwide. The massive Toronto underground pedestrian network is

30 km long and can be considered a city by itself (Bélanger, 2007). Japan has investigated the latest technologies in rock caverns and explored deep UGS (Tezuka and Seoka, 2003). In Northern Europe, a significant share of UGS function is for utilities infrastructures due to the energy efficiency of UGS (Bobylev, 2009). In recent years, a rapid and large scale underground space (UGS) development has taken place in different cities in China. In Beijing, there are 3 million m<sup>2</sup> of UGS being constructed each year (Chen et al., 2014). In Shanghai, over 68 million m<sup>2</sup> of UGS had been developed by 2014 (Zhao et al., 2016). The total underground construction area reached 19 million m<sup>2</sup> in Shenzhen in 2013 (Chen et al., 2013b). Guangzhou is building the

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largest underground complex in China (2.1 million m<sup>2</sup>), and the city is estimated to have 5 m<sup>2</sup> of UGS for each inhabitant by 2020 (Gao and Li, 2014). In the period 2011–2015 alone, over 2000 major underground projects have been constructed in China, with 100 million m<sup>2</sup> UGS put into service (Qian, 2016)

### 1.2. Research gap and research questions

Going underground has many advantages. For sites in the city center or Central Business District (CBD), savings in land costs can result in a much lower budget for an underground project than an aboveground one (Sterling and Godard, 2000). The temperature stability in UGS offers significant advantages in energy preservation (Zargarian et al., 2016). UGS can allow fast and clean public transport to replace air polluting motor vehicles (Besner, 2002). The development of UGS also contributes to eco-friendly developments by reducing the impact to the natural landscape in cities (Waterman, 2016). On the other hand, UGS is viewed negatively by the general population, who associate it with several environmental stressors and negative psychological effects (Roberts et al., 2016). The absence of natural light makes underground spaces less appealing, disregarding the fact that sufficient natural light is not provided in many above-ground buildings (Carmody and Sterling, 1987). The window-less environments of UGS could lead to a sense of confinement or claustrophobia (Al-Temeemi and Harris, 2004), whereas the lack of exterior reference points creates difficulties for spatial orientation and navigation in underground spaces can be confusing and difficult (Zhao and Künzli, 2016; Fontaine, 2001). Despite such common negative attitudes towards UGS, Durmisevic and Sariyildiz (2001) pointed out that these attitudes are more of a result of prejudices rather than concrete experiences, and suggested experimental research and post-occupancy evaluation as effective methods to identify design factors influencing the experience of UGS.

An increasing amount of research has been conducted to study UGS development in Chinese cities in recent years. He et al. (2012) studied the demand for UGS in urban districts. With the affecting factors being population density, GDP, and real estate price, the predictive model forecast an increasing UGS demand in future. Li et al. (2016a) studied the demand and driving factors for UGS in different cities. A study by Wang et al. (2013) concluded that development advantages of UGS, such as land use efficiency and environmental preservation, are the most important factors in terms of affecting the development potential of UGS among urban sub-districts. Guo et al. (2013) demonstrated new technology for land administration and UGS resource management in developed cities in China. Li et al. (2016b) argued the resource significance and sustainable development of UGS. Qiao and Peng (2016) analysed the possible causes for the existing problems in UGS in Chinese cities, such as low utilization rate and unbalanced functions of underground facilities, and lessons learned from successful practice were summarized. Huang et al. (2015) investigated possible factors causing geo-environmental hazards in underground structures and proposed several prevention and risk management measures. Li et al. (2013a, 2013b) defined the “underground urbanism” concept, and demonstrated how to support sustainable urban development by integrating the urban underground resources into the city-scale strategic planning.

Surprisingly, whereas previous studies provided important insights in UGS development, there is still a lack of close examination on the current usage of UGS, to provide a solid base and collective data for the establishment of guidelines and regulation for UGS development in China (Ministry of Housing and Urban-Rural Development, 2016). China has very clearly set up a national energy policy, including targets for emission reduction (Yi et al., 2011). To meet these targets, UGS development is important. One of the major characteristics of UGS is temperature stability. With little dependence on heating and cooling, UGS reduce energy consumption (Anselm, 2008; Bobylev, 2009). A previous study showed that the performance of underground structures

in controlling indoor temperature and energy saving is related to local climate (Givoni, 1998; Sobotka et al., 1996). It is necessary, therefore, to evaluate the energy performance of underground structures across different climate types in China. This will allow future developments to examine whether “one-size-fits-all” approaches are suitable, or, on the contrary, climate-specific standards and regulations should be adopted.

On the other hand, it is essential to understand the needs and preferences of UGS users. This is critical as it will largely determine whether people working in such spaces are happy, healthy and productive and thus willing to stay in such spaces. Additionally, UGS workers are the main communication drivers of the overall public perception towards UGS – if they have positive attitudes, then the public will also adopt more positive attitudes towards UGS. To examine these responses, we here adopt established methods borrowed from social sciences – methods that are rarely used in the field of tunnelling and underground space technology (van der Hoeven and van Nes, 2014; van der Hoeven and Juchnevic, 2016). These methods have been widely used in evaluating other aspects of urban design such as way-finding (Skorupka, 2008), train driving in urban areas (Naweed and Balakrishnan, 2013), and store design (Brenngman and Willems, 2009). Similar methodologies have previously been used to study questions of a narrower scope in UGS, such as mental mapping of underground pedestrian space (Vertesi, 2008), mobile technology for social interaction in UGS (Bassoli et al., 2007) or evacuation of UGS (Ge et al., 2011). We apply these methods to underground workers to offer recommendations for UGS design.

In the recently issued Thirteenth Five-Year Plan for Urban Underground Space Planning (Ministry of Housing and Urban-Rural Development, 2016), it is stated that by 2020, at least 50% of Chinese cities should: 1. Include the development of UGS into the Regulatory Planning for main districts; 2. Establish a comprehensive UGS system, to better manage UGS resource, planning, and construction at city-scale. To meet these targets, there is an urgent need for a feasibility study and pilot research to identify the key aspects to be investigated. This study is a qualitative investigation aiming to provide directions for future more quantitative research on the current status of UGS and occupants' attitudes towards such spaces as work environments. We here examine two important aspects: firstly, thermal comfort – a critical characteristic of UGS. How are the thermal performances of UGS in different climate zones in China? Is a one-size-fits-all approach to ventilation regulations suitable? Secondly, the preferences, responses and attitudes of occupants (workers) in UGS. In particular, what are the architectural characteristics or design elements of existing UGS that would be associated with positive and negative feedback from the occupants? A better understanding of both aspects will help in developing UGS that are more attractive to occupants and thus increasing their economic value. This is part of a larger, long-term research effort aiming to better understand human responses to UGS. We thus follow a systematic approach based on social science methodologies: typically, when examining a relatively unknown phenomenon it is preferable to start with a less restricted, open-ended approach that will identify the major themes and issues. Based on the outcomes of this research, more focused, well-controlled quantitative studies could help illuminate the underlying mechanisms and causal relationships.

## 2. Cities studied

An interdisciplinary team of psychologists, social scientists, engineers, and health experts visited different underground developments located in four Chinese cities, namely Beijing, Nanjing, Shanghai, and Fuzhou. These cities are at different latitudes between 26.07°N and 39.90°N, their background information is presented at Table 1. Shanghai and Fuzhou are coastal cities, Beijing and Nanjing are located in more inland areas of China (see Fig. 1). These four cities were chosen because they are relatively well-developed cities with substantial underground areas. Among them, Beijing and Shanghai are classified as

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