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Present status and development trends of underground space in Chinese cities: Evaluation and analysis

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ABSTRACT

With rapid economic growth and urbanization in recent two decades, the development of underground space in Chinese cities has made great progress, and the characteristics and development trends need to be re-examined. Though the existing urban development evaluation system is advanced, there is no commonly recognized underground space development evaluation index system. The correlations between urban indicators and underground space development, as well as between each underground indicator and the other, have not been comprehensively studied. Based on summarizing underground space evaluation indicators and the city indicators that affect underground space development, 12 indicators from categories of economy, society and underground are chosen to assess urban underground space (UUS) development. The 7 urban indicators that may affect the development of UUS include population density, per capita GDP, proportion of tertiary industry, industrial density, urbanization rate, investment in real estate development and car ownership. The 5 underground space indicators are underground space per capita, underground space per built-up area, underground parking proportion, proportion of service space in underground space, and underground space social dominant proportion. The data of 56 representative cities at different levels in 2015 is collected, normalized, shown in radar chart, and the correlation analysis are summarized. Based on sample analysis and other detailed works, four main conclusions of UUS developments in Chinese cities are put forward, including (1) the distribution can be broadly divided into three levels, and the structure is described as three cores, two axes, and one belt; (2) China is at the forefront of UUS development on aspects of UUS amount, Metro construction, underground complex construction, equipment and technologies and related industries; (3) the development is stimulated and promoted by urban development problems such as traffic problems, resource shortages and city resilience needs; (4) the development has a close relationship to city character and industrial structure. Three trends are concluded as new promoting roles in urban development in depth, new characterized development features, and increasing influence on urban forms. The paper provides a reference for scientific understanding and evaluation of the development of UUS in China, as well as for the promotion and regulation of UUS development through urban means.

1. Introduction

Underground resources development is regarded as an important measure to solve problems of urban population over-concentration, resource shortage, and environmental pollution. They also furnish a way to realize urban sustainable and compact development (Bobylev, 2009; Sterling et al., 2012), improve city resilience (Sterling and Nelson, 2013), and build a livable city (Hunt et al., 2016). In China, underground space is playing a vital role in the process of urbanization and modernization.

The reasons for the development of UUS in China changed with times. Early UUS development was mostly for storage, municipal and military applications (Pan, 2004; Waley, 1996; Wang et al., 1996). After the 1960s, some cities built large-scale underground shelters, and since then air defense facilities became the main form of UUS (He et al., 2012) until the 1990s. Since the mid-1980s, with the beginning of land leasing and paid-use policies and the rise of real estate, UUS began to develop rapidly (Tong, 2005). Passing into the 21st century, the level of urbanization in China increased from 31% in 1995 to 55.8% in 2015, and the urban population has more than doubled (UN Habitat, 2016). China's top ten cities account for 24% of the country's total GDP (Cadena et al., 2012). Social resources are more concentrated and

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enhanced in large cities. Under the impetus of urban space constraints, traffic congestion, environmental degradation and other issues caused by the rapid urbanization, UUS in China has entered a period of explosive growth. In recent years, UUS in the country has been increasing rapidly. Subways and underground parking, underground commercial streets and expressways are under widespread construction. Today, China has become one of the world's top countries with underground space development on many aspects such as subway and underground complex. The characteristics and development trends of underground space in Chinese cities need to be re-examined.

Many researchers have advanced indicators to evaluate underground space development, but there is no publicly accepted indicator system (Bobylev, 2010; Li et al., 2016). The current urban development evaluation system is relatively mature, but the correlations of underground indicators with ground ones, and correlations between each underground indicator and the other, still need to be comprehensively studied.

2. UUS development evaluation system

2.1. Methodology

Because UUS development is driven by urban problems and needs, there are two types of indicators that can be used to evaluate that development, i.e., UUS indicators and certain urban indicators closely related to UUS development (Fig. 1).

Step 1 – Review of UUS indicators and urban indicators that affect UUS development based on former researches.
Step 2 – UUS evaluating indicators selection, data collection, normalization and forms of presentation.
Step 3 - Selection of sample cities based on city representativeness (regarding economic zoning, economic developing status, city sizes, etc.), data reliability and availability.

China has more than 660 cities with substantially variable data on size, population, economy, and social development. This makes it difficult to present much information on a size-limited chart. For better comparison, we chose data with units of per capita, per unit area and per unit GDP, and built a radar chart format that makes it easier to understand city characteristics.

2.2. Evaluation indicators in existing studies

2.2.1. UUS indicators

UUS evaluation indicators usually include UUS capacity (Anttikoski et al., 1989; Jansson, 1976), average depth (Duffaut, 1980), average height of developed underground space (Duffaut, 1980), stratification of urban underground infrastructure (UUI) by depth (Duffaut, 1980), share of urban functions "on land" and "underground" (Bobylev, 2010), UUI distribution by depth (Bobylev, 2010), and UUS density (He et al., 2012). Bobylev (2016) advanced four main assessment indicators, that is, developed UUS volume, UUS use density, developed UUS volume per person, and underground premises floor area, indicating that the first three are more representative (Table 1).

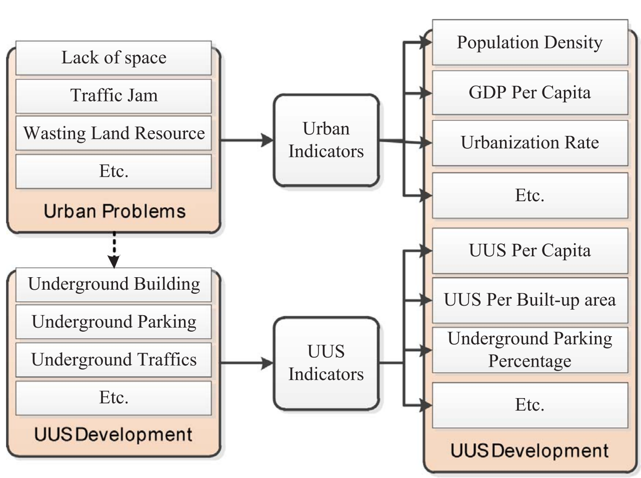

Fig. 1. Framework of UUS development assessment.

Table 1
Enabling data for Urban Underground Space (UUS) indicators (Bobylev, 2016).

Urban Underground Space (UUS) indicator/descriptor	Units	Units symbol
Developed UUS volume	Cubic meters	m^3
UUS use density	Cubic meters per land area	m^3/m^2
Developed UUS volume per person	Cubic meters per person (respective [urban] area population)	m^3/person
Underground premises floor area	Square meters	m^2

2.2.2. Urban indicators affecting UUS

Barker pointed out that China's civil air defense has impelled UUS development, and the urban construction department stipulated that a certain proportion of surface building funds must be used for subsurface construction (Barker, 1991). Golany and Ojima (1996) and Bobylev (2009)) argued that urban population and residential density are important drivers of UUS. Hunt et al. (2011) introduced an 'Urban Future' (UF) toolkit which explored possible uses for underground space within 4 plausible future scenarios in UK, and found that under the Market Force (MF) scenario greater use of underground space had occurred in urban areas due to a substantial increase in capacity requirements for transport routes and new utility connections. He Lei divided factors spurring UUS development into intrinsic and extrinsic ones, and regarded the urban economic and social system (including economic growth, population growth, urban sprawl, shortage of space, and traffic problems) of the extrinsic ones as factors shared by nearly all Chinese cities (He et al., 2012). He also concluded that population density and GDP per capita both have independent positive predictive power for the density of UUS use; the effect of real estate price is offset by these two factors. Liu (2009) analyzed statistical data and built a correlation analysis model, concluding that the intensity of UUS development has strong correlations with land price, plot ratio, and passenger flow. Cui et al. (2013a) suggested that the development of underground pedestrian space (UPS) is related to local climate conditions in cities such as Dalian, while in Shanghai and Hong Kong, it is traffic congestion and safety that are more important. Cui et al. selected 19 UPS cities as case studies to explore the prevalence of four influence factors, namely, weather, subway construction, economic level, and city scale. They found that the relative importance of those factors was 95%, 74%, 37%, and 26%, respectively. Li et al. (2013b) formed a rating system to identify cities with the potential for underground development, using four underground resources (underground space, groundwater, geomaterials, and geothermal energy) and three urban indicators (urban population, GDP per capita, and living density), in a management approach called the "deep city method". The authors also regarded land price and construction fees as main indicators in the evaluation of UUS economic efficiency (Li et al., 2013a). Xu (2014) concluded from statistical data that the main outer influence factors of UUS development in various regions were economic ones, e.g., GDP per capita, whereas inner factors were population density and vehicle ownership. Land-use characteristics are more important than building plot ratio in affecting UUS development. Bobylev (2016) compared UUS and the City Prosperity Index, finding that UUS is to some extent a symbol of city prosperity. After quantitative UUS data was examined for eight cities, positive correlation between urban population and developed UUS densities was discovered; there was less