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A GIS-based evaluation method of underground space resources for urban spatial planning: Part 1 methodology

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A R T I C L E I N F O

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A B S T R A C T

Urban underground space (UUS) has been playing an important role in the urban development in recent years. The evaluation for its potential becomes essential for urban spatial planning. Previous research emphasized the fundamental data, while this paper not only emphasized the data provided by related departments, but also took into consideration the gap and relation between UUS and urban spatial planning. To provide theoretical support for urban spatial planning, this paper studied a method for evaluating UUS. In this method, an index system for UUS resource evaluation was put forward and its analytical process was based on the Geographic Information System (GIS) and some mathematical tools, such as the analytic hierarchy process (AHP), the most unfavorable grading method (MUGM) and the exclusive method (EM). Then this method was applied to UUS Master Plans and Detailed Regulatory Planning in Chinese cities, and proved to be relatively practicable. The research outcomes are presented in the form of two papers, each with a different focus. Part 1 aims to introduce the evaluation methodology, including construction suitability evaluation & potential value evaluation & volume estimation. Part 2 reports on applications of the method to Chinese cities of Tongren and Changzhou.

Part 1 analyzed the concept behind and the process involved in the UUS spatial planning evaluation methodology, combining construction suitability evaluation & potential value evaluation & volume estimation. Based on the factors that influence the development and utilization of a UUS, an index system for UUS resource evaluation is presented. Its primary components are construction suitability (including landform, geology, hydrogeology and the existing construction situation) and potential value (including urban spatial location and land use function). Using AHP, MUGM and EM, the level of each index was quantified and overlaid based on GIS, and then the UUS evaluation output was obtained, such as construction suitability distribution, Resource's comprehensive quality (RCQ) distribution, with manifestation styles of maps and tables. In this research, three models are proposed, including a construction suitability model, a comprehensive quality model and a volume estimation model. The construction suitability model can evaluate the construction difficulty or cost grade, while the comprehensive quality model can evaluate potential benefit grade of every part in the city. They reflect the formula "Quality = Potential − Cost" to some extent. On the other hand, the volume estimation model can calculate the urban indicators for UUS, which can give data support for urban spatial planning.

1. Introduction

Urban underground space (UUS) is an important natural resource to be considered in the development of societies' economies and in the use of space in modern metropolises. UUS is not a renewable resource, because it is difficult to alter once being assigned to a specific function (Sterling, 1983). As urban space is rapidly extending underground and UUS planning is being or has been formulated in most cities in China, ways to evaluate UUS resources are needed. Thus, this paper aims at putting forward models to evaluate UUS resources.

The method proposed in this paper is intended for spatial planning of Chinese cities, so geothermal exploitation and geomaterials fall outside the scope of the research. This paper focuses on two aspects of planning, i.e., urban scale and land parcel scale (Li et al., 2013a) and presents a mapping method for evaluating the underground potential of urban areas with a particular focus on the role of geology, existing surface construction and urban planning factors. The method also explains and extends the evaluation of UUS in the cities of Changzhou (Peng et al., 2009, 2014) and Qingdao (Zhao et al., 2015). This paper is principally concerned with improving UUS resource evaluation modeling, synthetically considering major factors and applying GIS, AHP, the most unfavorable grading method (MUGM), and the exclusive

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method (EM) to establish a rational resource assessment framework. It aims to further theoretical methods and operational ways of determining UUS RCQ, and lastly provides theoretical support for UUS spatial planning. In the 2nd section, previous study is taken as the preparation for the evaluation framework establishment. In the 3rd section, evaluation framework is established and several mathematical tools and GIS analysis platform are presented. In the 4th section, the methodology is proposed including the overall mathematical evaluation structure, construction suitability evaluation model, potential value evaluation model and volume estimation model. In the 5th section, the applicable conditions and differences with previous study of the models are discussed. And the last section is the conclusions and the expectation encountered in the research.

2. Previous study

Substantial research has been done on UUS resource evaluation as a whole. Some cities or districts have made detailed plans for local zones and have performed early stage strategic research aiming at UUS development, but the methods by which these resources are investigated and evaluated vary widely. In an early investigation of conditions in Minneapolis, Minnesota, USA, geological conditions including the lithosphere, soil layer distribution, hydrogeology distribution, topographic slope, and space form were analyzed with respect to their suitability for UUS development. Spatial distribution and suitable exploitation forms for Minneapolis were also investigated (Sterling and Nelson, 1982). Another study in Australia reported that the most immediate opportunities for instituting planning efforts in urban areas lay in collating information on underground geological conditions and existing underground structures and facilities (Sterling, 1996). Using engineering geology database information and GIS systems, researchers have evaluated the objective conditions and difficulty of exploiting UUS (Boivin, 1990; Maurenbrecher and Herbschleb, 1994; Ronka et al., 1998; De Rienzo et al., 2007). Other studies have analyzed and classified the main factors affecting underground space development including geology, actualities, environment, psychology, society and economy, as they influence subjective and objective comprehensive assessment (Monnikhof and Krogt, 1998; Bobylev, 2005). Tong and Zhu (2009), focusing on urban geology and construction actualities, presented a macroscopic investigation and UUS evaluation system using GIS and a remote sensing system to analyze factors such as engineering geology, hydrogeology, and the space types of existing ground architecture. The volumes and depth of the underground infrastructure, as well as the functional uses of underground structures were considered in the Alexanderplatz area of Berlin, and an environmental assessment of underground construction technologies was performed with an Analytic Network Process (ANP) (Bobylev, 2010, 2011). Chen and Liu (2011) used landforms, regional tectonics, soil characteristics and hydrogeology to determine UUS RCQ classifications using fuzzy mathematics theory.

In recent years, further progress has been made in developing methods for evaluating and visualizing underground potential. He et al. (2012) proposed that population density and GDP per capita each have independent positive predictive power with respect to the density of UUS use. Wang et al. (2013) found that geological features, land price and location, economic development level, the advantages of developing underground space, and compatibility with urban planning are the five key influence factors that have positive effects on the development potential of UUS. Four underground resources, underground space, groundwater, geomaterial and geothermal energy are being developed by the Deep City project (Li et al., 2013a, 2013b), and a mapping method for UUS potential based on these four resources was applied in San Antonio, Texas, USA (Doyle, 2016). In Hong Kong and Shanghai, terrain data, geological maps, various land uses, underground installations, geological structures, boreholes and private lots were used to evaluate the cavern suitability of underground space, which provided a forceful gist for government decision-making (Wallace et al., 2014; Wallace and Ng, 2016; Qiao and Peng, 2016). One multilayer framework for evaluating the geological engineering suitability of UUS exploitation was presented and applied to a railway station area. It used a fuzzy analytic hierarchy process called the Technique for Order Preference by Similarity to an Ideal Solution (Lu et al., 2016).

However, despite the progress made by the various evaluations noted above, the general models still have several disadvantages and need to be improved, as shown concretely below.

(1) Some research is not practicable in UUS planning, especially for Chinese cities. Although several influencing factors have been suggested, some are difficult to collect before the UUS planning occurs. For instance, population distribution data, including where people live and where they work, is difficult to collect, even if the population of each district is known. However, the concrete distribution of where people live and work in each parcel and the routes they use to commute are key factors needed for spatial UUS planning. Those factors related to planning that can be collected easily should be taken full advantage of.
(2) The rational choice of factors to include in evaluations needs to be deliberated more seriously. Interdependencies or commonalities among elements in the hierarchy possibly exist but should be minimized (Saaty and Vargas, 2001), while some factors in previous studies are highly correlated with each other. For instance, land price is linearly correlated with transport conditions, because the better transport conditions are, the higher the land price is in most circumstances. Thus, perhaps land price and transport conditions should not be used simultaneously in evaluations. Similarly, population distribution is correlated with urban location and land use. Population generally concentrates in areas close to downtown and in residential or commercial land. Furthermore, a larger number of factors are not necessarily better. The evaluation should be limited to key factors influencing spatial planning that are not linearly correlated with each other.
(3) Some evaluation factors the analytic hierarchy process (AHP) method uses are not very rational. During evaluation, some factors may actually have one vote veto power. For instance, based on Chinese design codes, site stability determined by geotechnical features is key to planning, because even if other factors favor UUS development, an unstable site should be judged as unsuitable. Hence, not all factors can be properly gauged using the AHP method, and other complementary mathematical methods are necessary.
(4) Little of the extant research has considered the influence of building foundation depth. The area occupied by building foundations should obviously not be exploited as underground space. Thus, it is essential to analyze the depth of high-rise building foundations, especially at the land parcel scale, but previous studies have taken almost no account of building foundation depth.
(5) Little research has proposed using forward holistic volume calculation systems. This paper will present some key parameters for UUS volume based on GIS and mathematical methods.
(6) Few studies have presented the relationship between the comprehensive potential of UUS resources and spatial planning layout. This paper will show how the distribution of the comprehensive potential of UUS resources influences the layout and distribution of structures in spatial planning.

3. UUS resource evaluation system and methods

3.1. Evaluation system

Based on geological conditions, existing construction and urban planning factors, the UUS resource evaluation system is operationalized