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Research paper

Assessing quality of urban underground spaces by coupling 3D geological models: The case study of Foshan city, South China

Weisheng Hou [a,b,*], Liang Yang [a,b], Dongcheng Deng [a,b], Jing Ye [c], Keith Clarke [d,**], Zhijun Yang [a,b], Wenming Zhuang [e], Jianxiong Liu [f], Jichun Huang [f]

[a] *Department of Earth Sciences, Sun Yat-sen University, Guangzhou 510275, China*
[b] *Guangdong Provincial Key Laboratory of Mineral Resource Exploration & Geological Processes, Guangzhou 510275, China*
[c] *School of Public Administration, China University of Geosciences, Wuhan 430074, China*
[d] *Department of Geography, University of California at Santa Barbara, 1720 Ellison Hall, Santa Barbara, CA 93106-4060, USA*
[e] *Guangdong Geologic Surveys, Guangzhou 510080, China*
[f] *Foshan Bureau of Geological Survey of Guangdong Province, Foshan 528000, China*

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ABSTRACT

Urban underground spaces (UUS), especially those containing natural resources that have not yet been utilized, have been recognized as important for future sustainable development in large cities. One of the key steps in city planning is to estimate the quality of urban underground space resources, since they are major determinants of suitable land use. Yet geological constraints are rarely taken into consideration in urban planning, nor are the uncertainties in the quality of the available assessments. Based on Fuzzy Set theory and the analytic hierarchy process, a 3D stepwise process for the quality assessment of geotechnical properties of natural resources in UUS is presented. The process includes an index system for construction factors; area partitioning; the extraction of geological attributes; the creation of a relative membership grade matrix; the evaluation of subject and destination layers; and indeterminacy analysis. A 3D geological model of the study area was introduced into the process that extracted geological attributes as constraints. This 3D geological model was coupled with borehole data for Foshan City, Guangdong province, South China, and the indeterminacies caused by the cell size and the geological strata constraints were analyzed. The results of the case study show that (1) a relatively correct result can be obtained if the cell size is near to the average sampling distance of the boreholes; (2) the constraints of the 3D geological model have a major role in establishing the UUS quality level and distribution, especially at the boundaries of the geological bodies; and (3) the assessment result is impacted by an interaction between the cell resolution and the geological model used.

1. Introduction

Once cities expand to cover land areas with a mostly impervious surface cover, the three dimensional sub-surface volume becomes inaccessible for other uses. Nevertheless, the subsurface remains as a critical determinant of the future sustainability of an urban area, and the city's inhabitants are far from immune to the geological, geomorphological and hydrological structures that lie trapped beneath the urban concrete. Urban underground spaces (UUS), especially those with value as natural resources, are usually not considered in the planning of major cities, unless public works projects or hazards expose them and their risks. In China, the development of UUS will play a significant role in overcoming the overcrowding and traffic congestion in the process of urbanization (He et al., 2012; Shu et al., 2006), as it has in American cities such as Boston, with its "big dig" project.

UUSs have been the focus of increased attention in recent decades, because they impact urban functions and influence urban form, environment, transport, and energy use (Carmody et al., 1994; Bobylev, 2009, 2010; ITAWG13, 2004). Projects funded by government and local authorities in Australia (Sterling, 1997), the Netherlands (Edelenbos et al., 1998; Admiraal, 2006), and Japan (Japan Tunnelling Association et al., 2000) have investigated the potential for underground space use in their major cities. As a component of natural land planning, research about sustainable development of the UUS usually employs methods for the evaluation of land use sustainability. Urban environmental engineering needs and geological quality have usually been evaluated using multi-variate statistical analysis and GIS (Matula, 1981; Sakar et al.,

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[*] Correspondence to: Department of Earth Sciences, Sun Yat-sen University, B410 Dihuan Building, No. 135 Xingangxi Road, Guangdong Province, Guangzhou 510275, China.

[**] Corresponding author.

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2007; Turer et al., 2008). From the viewpoint of urban development and planning, urban land use and suitability have been assessed using fuzzy classification methods (Costa et al., 2011; Davidson et al., 1994; Hall et al., 1992; Van Ranst et al., 1996), multicriteria analysis (Pereira and Duckstein, 1993; Reshmidevi et al., 2009; Store and Kangas, 2001), ecological methods (Lathrop and Bognar, 1998); artificial intelligence techniques such as back-propagation neural networks (Xu et al., 2011), and by ant colony optimization (Yu et al., 2011).

These sustainability assessments have focused on aboveground development. However, addressing sustainable development requires a comprehensive understanding of both the quality of UUS and its related aboveground conditions. Multiple approaches to the evaluation of UUS quality have been proposed, such as qualitative analysis (Delenbos et al., 1998), the synthesis index method (Jiang et al., 2009), statistical methods (Bobylev, 2010; Sarkar et al., 2007), artificial neural networks (Lee et al., 2004; Xu et al., 2011), the fuzzy synthesis evaluation method (Wu et al., 2007) and the fuzzy set-based method (Wang et al., 2009). These approaches provide useful tools for the design and planning of UUS resources. More recently, 3D methods for estimating and visualizing the quality of UUS resources have also been proposed to support objective scientific planning and design (e.g., Jiang et al., 2009; Rienzo et al., 2008; Wang, et al., 2009; Wu et al., 2007). Several key factors such as geological features, and their locations, have direct impacts on the quality assessment of the UUS resources (Wang et al., 2013). Geological features are known to have positive impact on any final evaluation result (e.g. He et al., 2012; Jiang et al., 2009; Krogt, 1998; Sterling, 1997; Wang et al., 2013). However, the assessment of UUS resource quality is usually limited by sparse data about the geological features. Therefore, it is necessary to take full advantage of any existing geological data and knowledge in the evaluation process.

This research aims to integrate 3D geological models into the process of UUS resource quality evaluation and to explore the influence of the 3D geological model on the assessment results. We seek to develop a comprehensive approach using variable fuzzy-set methods, combined with a digital geological database and a 3D geological structure model. Our research focused on geological features that affect the quality of UUS natural resources. Here, the natural resources specifically means the soil, rock and structures, minerals, thermal energy, groundwater and some other resources are not included. Other important factors such as population, economics and other constraints were not taken into consideration. The case study in Foshan served as a tester for the proposed method of UUS quality assessment.

This research has two specific contributions to urban underground space research. On one hand, it facilitates a better understanding of the influence of uncertainties in the geological constraints on the quality assessment results. On the other hand, it offers guidance for constructing a factor evaluation system for UUS resource assessment so that authorities and planners can create better plans for UUS use.

2. Related work

Concentrated human activities and intensified land use drastically disturbs the environment, and the environment then impacts the engineering activities of human beings in return. Different methods of evaluating UUS resources have been presented from different viewpoints: of the quality (Delenbos et al., 1998; Wu et al., 2007), capacity (Bobylev, 2010; He et al., 2012), feasibility (Monnikhof et al., 1998) and sustainability (Bobylev, 2009). To make the most efficient use of UUS resources, their volume, structure and function should be incorporated into a master plans within cities (Belanger 2007; Bobylev, 2009; He et al., 2012). Thus, factors influencing the development potential of UUS should be investigated before excavation and construction, as is widely recognized by researchers, planners and authorities. In some developed countries like the Netherlands (Monnikhof et al., 1998), research on strategies has been carried out and the influencing factors for UUS resource assessment have been identified (ITAWG13, 2004; Krogt, 1998; Sterling, 1997). In China, some recent studies have attempted to investigate the influential factors in the development of UUS resources according to the different requirements (Jiang et al., 2009; Shu et al., 2006; Xu et al., 2011; Wang et al., 2009, 2013; Wu et al., 2007). Although the factors affecting UUS resources are changing constantly over time and with planners having different goals, five kinds of factors were identified from the existing literature about underground space. These were geological features, land price and location condition, level of economic development, development advantage of underground space and compatibility with urban planning, (Belanger, 2007; Jiang et al., 2009; Sterling et al., 2012; He et al., 2012; Xu et al., 2011; Wang et al., 2009, 2013). In the evaluation process, the assessment method embodies the interrelationships among those factors by map and attributes digitization. For example, the Analytic Hierarchy Process (AHP) decomposes the final evaluation goal into sub-goals with weights, and factors are grouped with weights at the bottom of the framework (Peng et al., 2010; Saaty, 1987). Rough sets (Pawlak, 1992; Wu et al., 2007) as well as Fuzzy-set theory (Jiang et al., 2005; Zadeh, 1965) allocate all factors weights on a plane. Experts usually give the factor weights during surveys, which subjectivity in the AHP method. Statistical techniques, like structural equation modeling, test and estimate the factor relationships using a casual assumption (He et al., 2012; Wang et al., 2013). Based on integrating values of each factor at various depths, two-dimensional approaches divide the volumes into just three or four parts in the vertical dimension, then calculate UUS quality using a grid partitioning in the planar direction.

In recent years, techniques for 3D geological modeling have made rapid progress and are widely applied in environmental assessment (e.g. Marache et al., 2009; Rienzo et al., 2008; Wycisk et al., 2009; Zhu et al., 2013). These techniques provide many kinds of methods for data organization, spatial partitioning, model construction and visualization in three dimensions. Supported by 3D spatial data models such as grid, grid+voxel, some 3D approaches have been used to evaluate the quality and sustainability of underground civil planning (Jiang, et al., 2005, 2007, 2009; Rienzo et al., 2008; Wu et al., 2007). In 3D assessment approaches, evaluations were applied to cells partitioned at depths using different and more accurate methods.

Two key shortcomings remain as challenges to UUS resource evaluation. First, the constraints and spatial configurations of geological outcrops have not been taken into consideration in the assessment process. In current research, geological features such as compression modulus are calculated using spatial statistics or other statistical methods. The background knowledge provided by 3D geological structure mapping is not taken into consideration in the interpolation to get values of different factors in the estimation process. As a result, we cannot get estimation results that are free from geometric uncertainties. Secondly, the distribution of uncertainty in the current estimation model plays no role. In reality, uncertainties caused by sparse data, imprecision and measurement error, stochasticity or imprecise knowledge (Bárdossy and Fodor, 2001; Cox, 1982) enter into the whole process of assessment. However, these uncertainties have not been taken into consideration in the UUS assessment process.

3. Data and method

3.1. Study area

The study area is a 35 km^2 area centered on the city of Foshan, located to the north of the Pearl River Delta in Guangdong province, south China (Fig. 1). Most of the study area is covered by Quaternary strata. Some hill monadnock and residual platforms distributed sparsely in Foshan city. Geologically, the study area lies to the southeast of the Sanshui downfaulted basin that has formed since the early Cretaceous, and as a whole is tilted monoclinically from east to northwest (Wang et al., 2006). This basin has been affected by faulting and magma intrusion, causing local deformation and over time has formed a limited drag or rolling fold. The fracture structure is still under development. Regional faults, including northeast faults like the Guangzhou–Conghua fault zone and the Shunde–Dongguan fault zone, and northwest faults such as the Baini–Shawan fault zone and the Beijiang fault zone, are located throughout the study area. These faults have formed a varied but orderly fracture structure pattern throughout the downtown area of Foshan city.

Quaternary strata formed during the Lonian, Tarantian or Holocene are widely distributed in the study area. The compositions of quaternary strata are complex and change over short distances laterally. According to borehole information, the thickness of the quaternary strata in the study area varies significantly, from 10m to more than 60 m. The sedimentary center dips northwest and is impacted by the northwest faults.

3.2. General approach

In this study, variable fuzzy set theory as proposed by Chen (2005) was used to evaluate the UUS resource quality. The original fuzzy set theory proposed by Zadeh (1965) which dealt with uncertainties and allowed the incorporation of the opinions of decision makers, can easily solve the problems of incompleteness in the quality evaluation of UUS resources. In fuzzy set theory, each element is assigned degrees of membership on a gradual scale in the real unit interval [0, 1] with the aid of a membership function. The membership functions can be defined on the standard function types determined from data by semantic import model. When the membership function of Fuzzy sets take values 0 or 1, the indicator functions of classical sets become special case of Fuzzy sets. However, the relative nature and dynamic adaptability of the essential variables were not taken into consideration in classical fuzzy set theory, which assumes that fuzzy membership functions are absolute and unique (Li et al., 2012). Based on opposite fuzzy sets and the definitions of a relative difference function, the theory and method of variable fuzzy set (VFS) was proposed by Chen (2005) and Guo and Chen (2006). Research has shown that variable fuzzy set theory better represents the quantitative description of variable fuzzy sets by defining a relative difference function and a relative membership function. This avoids the complicated problem of selection and application of the membership function in the fuzzy comprehensive evaluation method. Further, successful applications of this approach already exist for the evaluation of the quality of UUS resources (Jiang et al., 2009), for water pollution

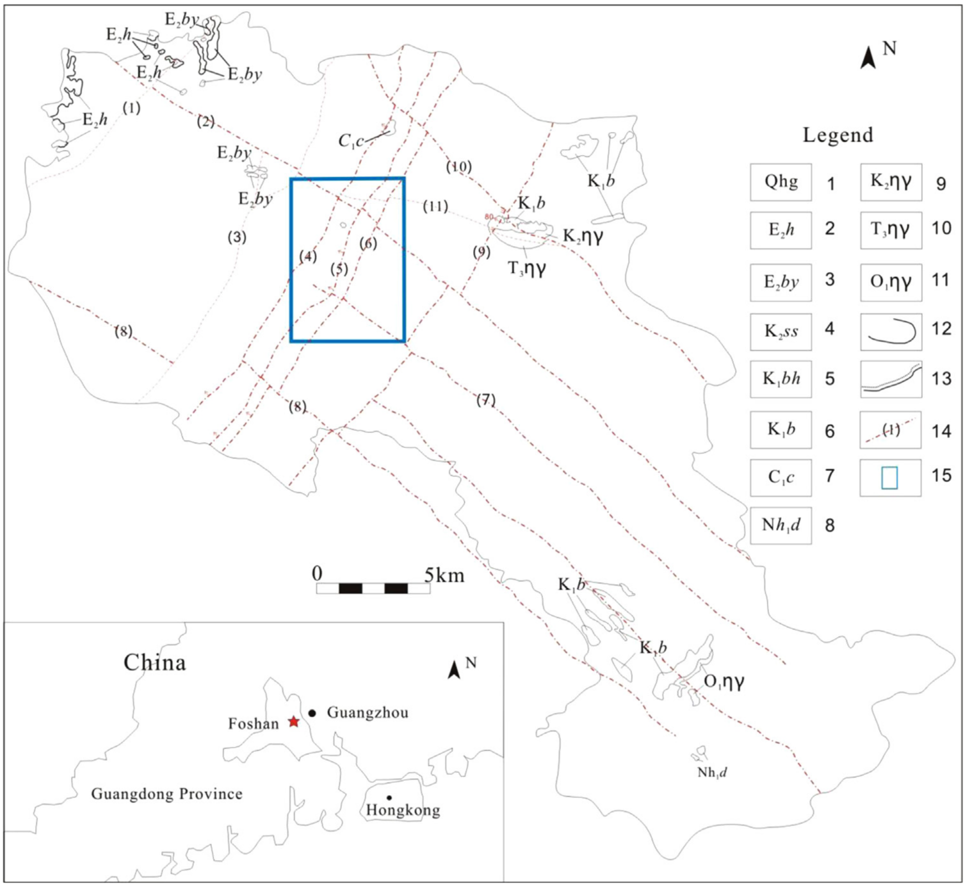

Fig. 1. Geological tectonics chart of the Study area (after Guangdong Geological Bureau, 1988). 1. Guizhou group of Holocene; 2. Huachong group of Eocene; 3. Baoyue group of Eocene; 4. Sanshui group of Late Cretaceous; 5. Baihedong group of Early Cretaceous; 6. Baizushan group of Early Cretaceous; 7. Ceshui group of Early Carboniferous; 8. Daganshan group of Early Nanhua period; 9. Granite of Early Cretaceous; 10. Granite of Late Triassic; 11. Granite of Early Ordovician; 12. Geological boundaries; 13. Unconformity geological boun daries; 14. Buried fault; 15. Study area. (1) Shijie-luocun Fault; (2) Zumiao Fault; (3) Shanzi Fault; (4) Leigangxi Fault; (5) Leigangdong Fault; (6) Wuyanqiao Fault; (7) Foshangang Fault; (8) Xijiang Fault; (9) Guangcong Fault; (10) Baini–Shawan Fault; (11) ShiBei Fault.

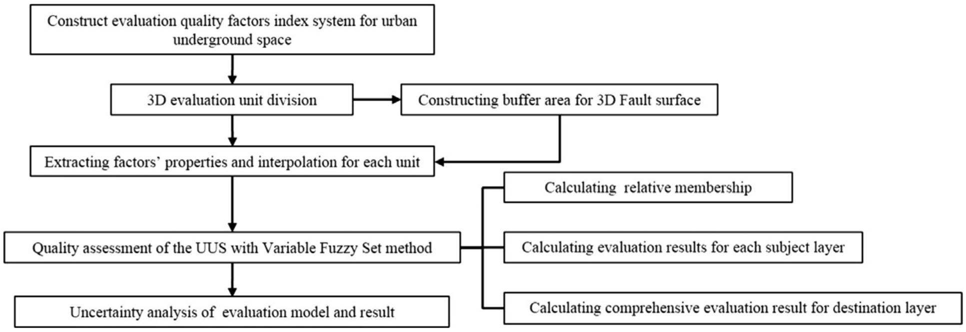

Fig. 2. Flowchart of UUS quality assessment.

assessment (Ma et al., 2012), for river health system evaluation (Qin et al., 2012), for flood risk analysis and evaluation (Li et al., 2012) and for the quantity, quality, regeneration and carrying capacity evaluation of water resources (Chen, 2005; Chen and Hu, 2006; Chen et al., 2007). Consequently, variable fuzzy set theory was used in this study to avoid membership function choices in the evaluation process.

In the present study, VFS was combined with AHP method as an integration of techniques. The presented method uses fuzzy multiple indicators of comprehensive evaluation of VFS and converts the multiple indicators of the samples into one-dimensional degree values. The basic method of fuzzy set-based 3D quality assessment for UUS resource included several steps (Fig. 2). First, the factors index system was constructed using the AHP (Saaty, 1987) on the geological features of the study area. According to the basic idea of the AHP, the final objective was decomposed into a hierarchy of three layers' themes. Every element of the hierarchy was allocated a numerical weight that represented the relative meaning and importance. Secondly, the evaluation units for UUS resources were divided into cells according to a 3D Voxel model (Marschallinger, 1996). The whole studied area was partitioned into cells and the quality assessment of the UUS was implicated on these cells. At the same time, 3D buffer areas were constructed for all fault faces that were extracted from the 3D geological model. Third, every factor's property at every vertex of each geological unit was extracted by interpolation assuming that factor attributes within each cell were considered as homogeneous. Here, the 3D geological model was introduced into the interpolation process as a kind of constraint because the 3D geological model constructed in this study is a structural model rather than an attribute model. During the assessing process, the 3D geological model is a very important element. For example, the value of fault factor is decided by the fault level and the distance between the vertex and corresponding faults, in which fault surfaces are extracted from the 3D geological model. The 3D geological model was used in the second and third step, in this study, and this will affect the final results because the rest steps relied on the Variable Fuzzy Set method have nothing with any factors or models. Fourth, quality assessment of the UUS was implemented with the Variable Fuzzy Set method, in which three parts are included. Based on the variable fuzzy set theory, a relative membership grade matrix of the evaluation factors was constructed, and the relative membership functions were calculated. Then, the evaluation results for each subject layer were obtained from the normalized relative membership grade matrix. A comprehensive evaluation result for each destination layer was calculated according to the subject layers. Fifth and finally, the indeterminacy of the evaluation result was analyzed. Although we followed the basic steps of variable fuzzy set method proposed by Chen (2005), what we are concerned of in this study is how to calculate the weights for those factors more reasonably and take geological conditions into the factors interpolation. Here, entropy weight method was used to calculate the weight coefficient of every factor in the soil condition rather than consistency theorem of taxis (Chen, 2005) or information diffusion (Li et al., 2012). We will discuss each step in detail in the following section.

3.3. Data collection and 3D geological model of the study area

We collected 475 borehole samples and their related test data, a map of bed rock and a remote sensing image of the study area. Most of the boreholes were drilled for engineering geological analysis and Quaternary analysis. Physical attributes such as density, water content, angle of internal friction, liquidity index, and modulus of compression were tested for loose deposits. Rock mechanical parameters such as compressive strength were tested. The stratigraphic divisions were given for each borehole according to lithological information and test data. All of these data were stored in a geological database. The values of soil and rock mechanical parameters of the borehole samples provided the necessary data for the quality assessment of the UUS resource in the study area.

To reveal the extent of geological bodies underneath the study area, 6 intersected cross-sections were drawn according to the stratigraphic divisions of the related boreholes (Fig. 3). The whole study area was divided into four sub-areas. In each sub-area, geological bodies were built by connecting the geological boundaries at cross-sections. The 3D geological model was built within the MapGIS®[1] software (Chen et al., 2011). Although it is manual and time-consuming, the method can keep topology correct and make the best use of geological knowledge in the modeling.

3.4. Establishment of the factor index system for UUS evaluation

Quality evaluation of the UUS resources was based on a systematic combination of the interactions among the different factors including engineering conditions, hydrological conditions, 3D geology, faults and other factors as well as above ground conditions. As mentioned above, we focused on discussing the geological features impacts on the quality of the UUS resource, so other kinds of factors were excluded in the factor index construction and furthermore, the landscape condition was not taken into account because the landscape of the study area is mostly flat and without hills.

All the factors that affect the quality of the UUS resources are interrelated and interact with each other to form a complex system. Synthetic analysis of the effect of the factors and evaluation of the quality of the UUS resources influence the final result directly. Therefore, determining the weight of the factors also should be concerned seriously according to their compacts. In the current

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[1] www.mapgis.com.cn

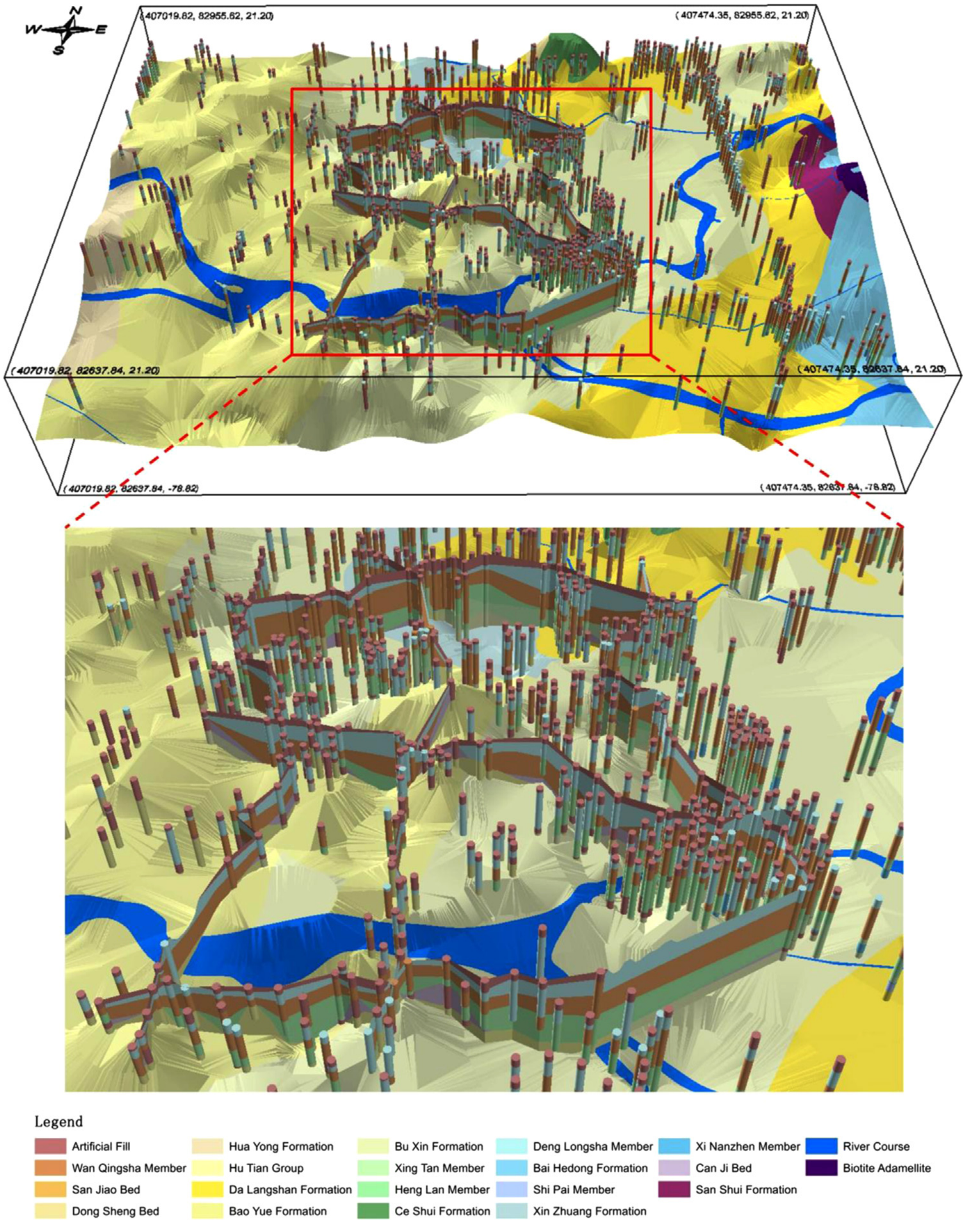

Fig. 3. Geological data collected in study area. The cylinders are boreholes, the fence parts are cross-sections and the TIN surface is bedrock map. The Guizhou group of Holocene in Fig. 1 includes three members: the Wanqinsha member, the Denglongsha member and the Henglan member.

Table 1
The index system and corresponding weights of each index.

Object layer	Subject layer (weight)	Index (weight)	Characteristics
Urban underground space quality	Soil condition (0.5)	Specific gravity (0.206)	Quantitative
		water content (0.19)	Quantitative
		angle of internal friction (0.213)	Quantitative
		Liquidity index (0.17)	Quantitative
		Modulus of compression (0.221)	Quantitative
	Bedrock condition (0.3)	Intensity of weathering (0.4)	Qualitative
		Compressive strength (0.6)	Quantitative
	Fault (0.2)	Fault activity and level (1.0)	Qualitative

study, the AHP is used to solve this problem. The AHP formulates the decision problem in a hierarchical structure and takes multiple options and criteria into consideration. This is especially suitable for problems of evaluation. According to the principle of the AHP method, the index system for quality evaluation of the UUS resources was constructed with three input layers (Table 1). The target layer is the final goal of the quality evaluation of UUS resources, representing the final quality values. The subject layer is subdivided into three parts: soil condition, bed rock condition and faulting conditions, according to the relationship among factors for evaluation. The hydrological conditions – such as depth of groundwater table, the corrosive potential and possible groundwater – were very vital in the assessment. We excluded these parameters in the subject layer because only a few hydrologic samples were available for the study area. The index layer was derived from all of the qualitative and quantitative factors. We invited 10 geologists and engineers from Foshan Bureau of Geological Survey of Guangdong Province and Guangdong Geologic Surveys to determine the indexes. With hands-on experience of the underground space of the study area, these specialists are considered competent to evaluate the influence of the factors. Also, to reflect the differences among the geological conditions for the UUS resource quality, the factor weights in the subject layer were referenced to expert opinions.

In the study area, the Quaternary deposit with maximum depth of nearly 60 m is the main potential development area. Soil condition is the main factor in the study area and it was assigned the maximum weight value. Although fault activity is a very vital factor in UUS resource development, the weight value was relatively low because the samples from boreholes revealed that faults do not cut into the Quaternary strata. The qualitative factors in the index layer were quantified according to experts' experience and judgment. The weight value of fault activity and level was 1.0 because the fault layer is only one factor in the index layer. The bedrock condition layer is composed of intensity of weathering and compressive strength. Actually, the intensity of weathering and compressive strength are two related factors. If the rock is fully weathered, the value of compressive strength is very low and vice versa. However, some rock samples described the weathering condition rather than the test value of the compressive strength. Therefore, we put them together. The weight coefficient of every factor in the soil condition was calculated by the entropy weight method, to reflect the differences and relationships among the evaluation factors.

Information entropy was first defined by Shannon (1948) and was used as a measure of the missing information. According to the method presented by Jiang et al (2009), the entropy weight method can be calculated by the following steps. First, a normalized judgment matrix $B = (b_{ij})_{mn}$, $b_{ij} \in [0, 1]$ for indexes is constructed, where b_{ij} are the values of index j that belong to grade i, n is the number of indexes and m is the grade level of each index.

Suppose that the sample set is $\{x_1, x_2, \ldots, x_n\}$ and every sample has m indexes, the sample indicator matrix is $X = (x_{ij})$, where x_{ij} is the ith index of sample j, $i = 1, 2, \ldots, m$, and $j = 1, 2, \ldots, n$. If each index can be evaluated by k levels, the index criteria interval matrices of each level are presented as $I_{ab} = ([a_{ih}, b_{ih}])$, and for each $[a_{ih}, b_{ih}]$ we determine its range of interval $[c_{ih}, d_{ih}]$ according to the lower and upper limits, where $i = 1, 2, \ldots, m$, $h = 1, 2, \ldots, k$, and $[a, b]$ and $[c, d]$ are repelling sets of variable fuzzy set (Li et al., 2012). According to Chen (2005) and Li et al. (2012), thus, we obtain the relative degree of the membership matrix of the index values of the sample to each level as follows:

$$\mu(x_{ij}) = \begin{cases} 0.5\left[1 + \left(\dfrac{x_{ij} - a}{M - a}\right)^{\beta}\right] & x \in (a, M) \\[2ex] 0.5\left[1 - \left(\dfrac{x_{ij} - a}{c - a}\right)^{\beta}\right] & x \in (c, a) \end{cases} \tag{1}$$

, or

$$\mu(x_{ij}) = \begin{cases} 0.5\left[1 + \left(\dfrac{x_{ij} - b}{M - b}\right)^{\beta}\right] & x \in (a, M) \\[2ex] 0.5\left[1 - \left(\dfrac{x_{ij} - b}{d - b}\right)^{\beta}\right] & x \in (c, a) \end{cases} \tag{2}$$

where M is the point where its value of relative difference function equals 1 in attracting sets $[a, b]$, and β is the index bigger than 0, usually taken as $\beta = 1$. Then, the normal judgment matrix can be obtained as

$$B = (b_{ij})_{mn} = ((\mu(x_{ij}) - \min(\mu(x_{ij})))/(\max(\mu(x_{ij}) - \min(\mu(x_{ij})))_{mn} \tag{3}$$

Next, the entropy of each index is given by

$$H_j = -\frac{1}{\ln m}\sum_{i=1}^{m} f_{ij}\ln f_{ij},\; f_{ij} = \frac{1 + b_{ij}}{\sum_{i=1}^{m}(1 + b_{ij})}$$
$$(i = 1, 2, \cdots, m;\; j = 1, 2, \cdots, n) \tag{4}$$

Finally, the entropy-weight of each index w_j can be calculated as follows:

$$w_j = \frac{1 - H_j}{\sum_{j=1}^{n}(1 - H_j)},\; \sum_{j=1}^{n} w_j = 1 \tag{5}$$

This yields entropy-weight values for all indexes of soil conditions as shown in Table 1.

The AHP and the VFS are integrated to develop a fuzzy analytical hierarchy process to decide the quality of synthetically degree value, because of the vagueness and uncertainty existing in the sample data. The presented method incorporates the experts' subjective judgment, if need be, during the analysis by expressing the complex system in a hierarchical structure. Therefore, AHP ensures that the evaluation process is systematic, numerical, and computable, which is recognized as a robust and flexible tool for dealing with complex decision-making problems (Liang et al., 2006).

3.5. Underground space division and extraction of the properties

The spatial partitioning of the UUS is the foundation for quality evaluation. The smallest unit for quality assessment of a UUS resource was termed a "basic cell". It contains the median of all index values, geological attributes and evaluation results in that cell. Furthermore, the estimation process is carried out at the vertexes of the basic cells. The size and precision of the basic cell determine the accuracy of the quality estimation result. Therefore, it is essential to divide underground space objectively during the evaluation process.

A hybrid model of grid+voxel was used for partitioning the UUS (Jiang et al., 2007, 2009; Wu et al., 2007). The Grid model is much more convenient to analyze and quantify the evaluation results than an irregular model. The Voxel model can break through the limitations of the Grid model by the representation of the major resolution difference between the vertical direction versus other two directions. For example, the estimation may cover several thousand square kilometers, while the depth is less than 100 m; so, the basic cell cannot be a cube. The study area was divided into 9176 raster cells with a grid size of 5 s × 5 s × 5 m based on the Voxel model.

The quality assessment of UUS resource was computed on a cell by cell basis. Before the evaluation process, the properties of the evaluation factors on each cell were obtained. Unfortunately, the geological data are usually sparse and not all vertices have corresponding values for the evaluation factors. Therefore, spatial interpolation was an important step in the evaluation process. Before the interpolation of evaluation factors, those qualitative factors on the same vertexes were assigned values according to the assigned classification. Then, all factors' values on each basic cell's vertices were interpolated by Co-Kriging.

Of concern in the interpolation process is the cross effect of known attributes on different geological bodies to those interpolated attributes on vertices of the basic units. Theoretically, the sample data of known attributes should be in the same geological body where the interpolated vertex was enclosed. However, the basic method of Co-Kriging does not take this into consideration. In this study, a 3D geological model of the study area was introduced into the interpolation as a constraint. Those sample data outside of the geological body where the interpolated vertexes were located were not included. If one geological body such as a lenticle is so small that it just encloses one sample, the interpolation process of those vertexes was skipped and the factors' values on those vertexes remained the same as the samples'.

3.6. *Buffering of three-dimensional faults*

Faulting is an important factor in the quality estimation of UUS. To simplify the problem without loss of generality, faults are often modeled as geometric surfaces with zero thickness. In fact, faulting not only changes the geometry of a geological body, it also changes the physical attributes of adjacent rocks. However, most literature has focused on the reasonable quantification of the faulting factor. Instead, we proposed that the index value of faults on those vertexes in the influenced zone should be digitized in a particular way, instead of just considering the natural neighborhood vertexes of a given fault.

In this study, faults were reclassified into Level I to Level V as other factors do, according to the scale and activity of the fault. As shown in Table 2, each fault was assigned one level and an impacting distance. The level I fault has the shortest impacting distance and Level 5 has the longest distance. A 3D buffer volume of each fault was created by assigning a degree of influence in accordance with the fault hierarchy. The buffer volume spreads only along the x and y directions. The index value of the fault on each vertex in the included zone varies inversely with the distance between the vertex and the fault, which means that the maximum index values distribute along the fault surface and index values on those vertexes away from the fault decrease linearly with the distance from the fault surface. In the area of several faults impacted, the index values on those vertexes are summed directly from those index values of each faults. For example, three faults A, B, and C with levels V, IV and I respectively cross together on the same area. Given that the index values of these three values are 1, 0.8, and 0.2, the index value on the vertexes that three faults cross is 2.0 ($1.0+0.8+0.2$). Therefore, impact of all faults can be digitalized. Then, the index values of all faults can be normalized and reclassified as five levels in the whole evaluation volume. On the conjunction of several faults, the quality is worse than other areas because rock is subjected to multiple stresses as shown in Fig. 4. Hence, fault influence can be described according to the hierarchy and scope of the influence of the fault in numeric. Index values faults on those vertexes out of impacting scope of faults are zero.

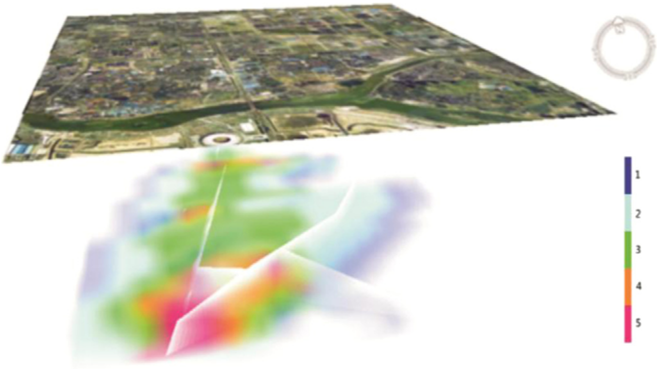

Fig. 4. 3D fault buffer and its evaluation. The color scope is the impact area of faults. Different colors show the index value of faults on the vertex. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.7. *Variable fuzzy set method*

Generally, three steps formed the process of evaluation with the variable fuzzy sets method put forward by Chen (2005) and as described in some literatures such as Guo and Chen (2006) and Li et al. (2012). First, a hierarchical set of estimation factors was constructed according to engineering needs. Secondly, relative membership functions and the relative degree of membership were built for each factor. Lastly, the weight vector of factors was calculated, such that the sum of all members of the vector was equal to 1.0.

Grading standards for UUS evaluation were constructed according to the index systems shown in Table 1. The grading standards for quantitative factors such as specific gravity, the liquidity index, and the modulus of compression were easily classified (Table 2). Although the intensity of weathering of the bedrock was a qualitative factor, it was described using five levels (Table 2): fresh rock, slightly weathered, moderate weathering, strongly-weathered and completely weathered in the database. Therefore, the grading standards of the intensity of weathering of bedrock do not need to be classified precisely. In reality, geological specialists should mark the activity and level of each fault before the factor is enumerated. In this study, the faults were classified into five grades: level I to level V. The higher the level value, the more intense the activity of the fault is and the smaller the influence scope will be. Hence, a fault with level I has the lowest quality and a fault with level V has the best quality.

We notate the set of vertices in the UUS evaluation as $\mathrm{x}=\{x_1, x_2, \ldots, x_\mathrm{n}\}$, where n is the number of vertices, then the characteristics of the jth vertex can be denoted as $x_j=\{x_{1j}, x_{2j}, \ldots, x_{mj}\}$ where m is the number of UUS evaluation factors. Next, we denote $\mathrm{X}=(x_{ij})$ as the vertex set with an $m\times n$ order matrix. The variable fuzzy set evaluation model can then be denoted as follows (Chen, 2005; Wu

Table 2
Grade standard of indexes.

Index	Grade standard				
	I	II	III	IV	V
Specific gravity	>2.85	2.85–2.65	2.65–2.45	2.45–2.25	<2.25
Water content (%)	<20	20–30	30–50	50–60	>60
Modulus of compression (MPa)	>40	40–30	30–10	10–5	<5
Angle of internal friction	>60	60–50	50–39	39–27	<27
Liquidity index	<0	0–0.25	0.25–0.75	0.75–1	>1
Intensity of weathering	Fresh rock	Slightly weathered	Moderate weathered	Strong weathered	Completely weathered
Compressive strength (MPa)	>60	60–30	30–15	15–5	<5
Fault activity and level	Level V	Level IV	Level III	Level II	Level I

et al., 2007):

$$u'_f = 1/\left(1 + \left(d_{gf}/d_{bf}\right)^{\alpha}\right)$$

$$d_{gf} = \left\{ \sum_{j=1}^{m} \left[w_j\left(1 - \mu_A(x_{ij})_f\right)\right]^p \right\}^{1/p}$$

$$d_{bf} = \left\{ \sum_{j=1}^{m} \left[w_j \mu_A(x_{ij})_f\right]^p \right\}^{1/p}$$

where u_f' is the non-normalized synthetic relative membership degree of grade f, α is the optimization parameter, $\mu_A(x_{ij})_f$ is the relative membership degree of grade f, m is the number of evaluation factors, w_j is the weight of each factor, d_{gf} and d_{bf} are respectively the maximum and minimum relative membership degrees that can be calculated by the method shown in the literature (Chen, 2005; Guo and Chen, 2006; Li et al., 2012) or by the formula (1) or (2), and p is the generalized weighted distance for which the value is 1 or 2.

Then, the normalized synthetic relative membership degree can be calculated as follows:

$$U = \sum_{f=1}^{c} Fu'_f \tag{7}$$

where F is the eigenvalue matrix and c is the number of the grade. In this study, the final result of UUS quality evaluation was obtained based on formula (7).

4. Results and discussions

According to the distribution of boreholes in the study area, the evaluation volume was divided into 9176 cells with the grid 5 s × 5 s × 5 m. Fig. 5 shows the final result of the UUS quality evaluation. The green part (level III) with a purple zone (level IV) nested within occupied most of the volume of the study area (Fig. 5(a)). Other grades of soil quality were scattered throughout the study area. Soil of grade V is absent from the study area. According to the result of the bedrock condition (Fig. 5(b)), the grade of the upper layer is IV. The qualities of other areas are much better and appear unrelated to landscape orientation. The quality grade is greatly reduced in the fracture intersection areas (Fig. 5(c)). For example, the quality grade tectonic conditions are V in the intersection area of the three faults shown in Fig. 5(c). In general, the volume of quality grades III and IV (34.4%) occupy most area (Fig. 5(d)). The areas with grades I and II are dispersed. In the vertical direction, the quality in the lower part is better than the upper part overall.

4.1. Scale effect of evaluation result

We assumed that geological attributes in each cell are homogeneous. However, attributes after aggregation or grouping in different scale cells will affect the evaluation results to varying degrees. In this study, three cell sizes with grid 5 s × 5 s × 5 m, 10 s × 10 s × 5 m and 20 s × 20 s × 5 m are selected for a cross-scale assessment. The average distance between boreholes is about 10 s. Therefore, we can analyze the relationship between cell size and sampling distance and its impact on final evaluation result. The parameters and data were the same as those in Section 2. Without the constraints of the 3D geological model, the spatial distribution of the difference between the evaluation results at different cell sizes was analyzed. The comparison results are shown in Fig. 6 and in Table 3.

On the top of the red area, the volumes of level IV (the purple volume) and Level II (the light blue volume) behind the Level I (the dark blue volume) shrank as the cell scale decreased (Fig. 6(a)–(c)). A small volume of Level V was shown in Fig. 6(a) while others results with different scales did not show up in the same area. Another interesting thing is that, in the red circle area, Level I has the largest volume when the cell scale is 20 s × 20 s × 5 m (Fig. 6(a)–(c)) and the minimum value is shown when the cell scale is 10 s × 10 s × 5 m. The same situation showed up in the proportion of different grades shown in Table 3. Assuming that the assessment volume is a constant, the percentage of volume that belongs to different quality grades is given by the proportion of cell

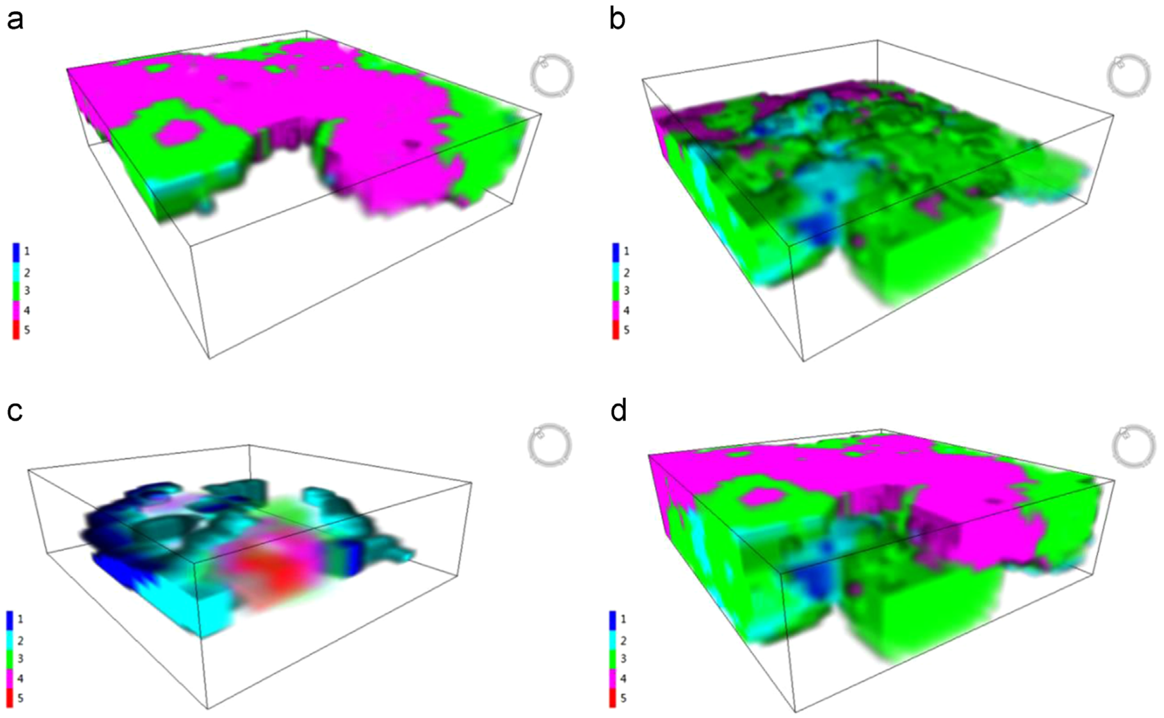

Fig. 5. UUS quality assessment results without strata constraints. (a) Quality assessment of soil condition; (b) quality assessment of rock condition; (c) quality assessment of faults; and (d) the final assessment result. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

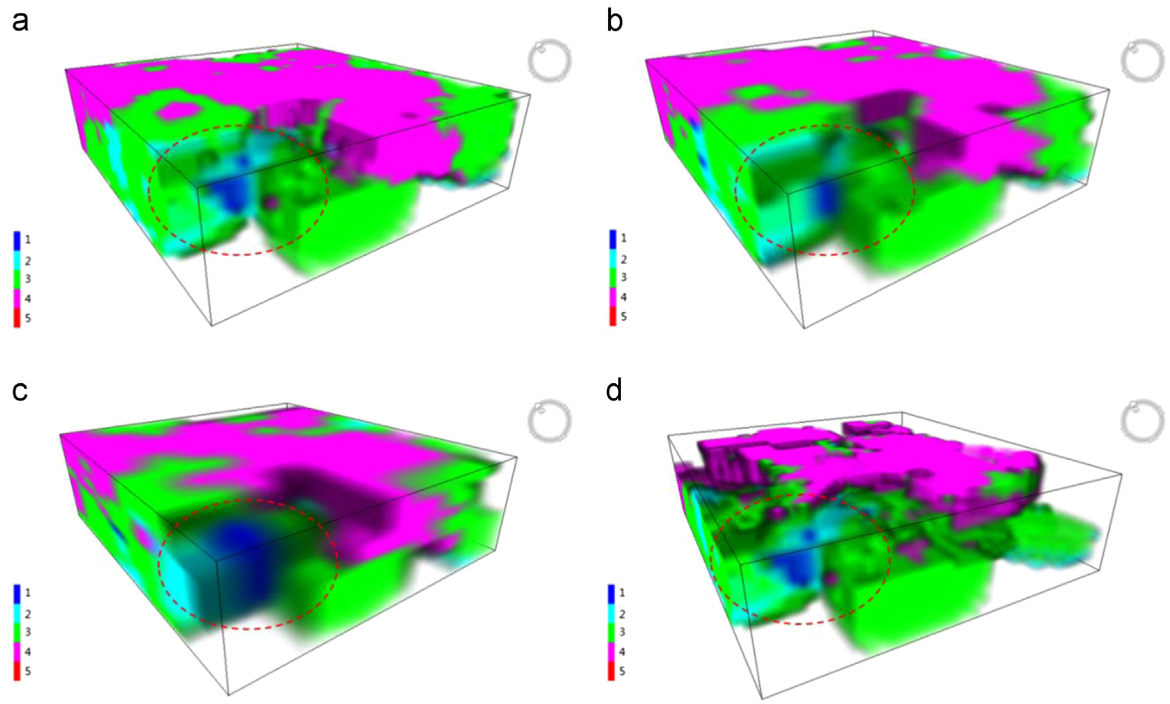

Fig. 6. Comparison of UUS quality assessment results with different cell scales. (a) 5 s × 5 s × 5 m; (b) 10 s × 10 s × 5 m; (c) 20 s × 20 s × 5 m; and (d) the final assessment result with strata constraints, in which the cell size is 5 s × 5 s × 5 m. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

numbers. According to Table 3, the volume of level III decreased as the scale increased. However, the situation of level IV has the opposite trend. The volume proportion of levels I and II changed in volatility and the difference was large. In general, whatever the scale, level III and level IV occupied the bottom and top volumes. The volume of level II sits in the space among level III and level IV and the volume of level I is embedded in the space of level II. The space shape of each level changes when the cell scale varies. Especially, the distribution of each level changes most near the strata boundaries.

4.2. Uncertain analysis in the extraction of properties

Each stratum has different physical properties. Without taking into consideration the strata distribution, properties of those cells near the boundaries might be disturbed by the neighboring strata when interpolating the values for each cell. Therefore, constraints at the faults and strata should be introduced in the interpolation. In this study, during the process of interpolation, the sample data were strictly selected from the geological body that contained the interpolated cell. Two assessment results with the same cell size are given in Fig. 6(a) and (d). Fig. 6(a) is the assessment result without constraints and Fig. 6(d) is the result taking into consideration the faults and strata constraints. The 3D model of quaternary sediments in the study area is built on cross-sections shown in Fig. 3. Therefore, the boundaries of evaluation volume are irregular and also limited the space distribution evaluation results apparently (Fig. 6(d)). The depth of level IV (the purple area) in Fig. 6(d) on the top of the red circle is shallower than that in the same area on Fig. 6(d). On the right part of red circle, the green volume in Fig. 6(d) took the place of the purple one in Fig. 6(a). This means that the boundary constraint has a serious impact on the final results. The boundaries of each grade are constrained by the shape of the geological bodies. To explore the influence of constraints impact on the result, the Wanqinsha member was extracted as an example. Fig. 7 shows the comparison of the assessment results of the Wanqinsha member with different interpolation constraints. In Fig. 7, the northern green part showed up in the right picture while it was covered by purple in the middle picture. Also, the volume of the cube in the south in the middle picture is obviously larger than that in the right picture. The cell numbers show the difference directly in Table 4. The number of cells of Level III without the constraint is 177, while this number increased up to 404 with the constraint. Under the conditions of strata constraints, the volume of level III increased while level IV's decreased because the total volume is a constant.

The 3D geological model used in the evaluation was a coarse model. Although it is built on the basis of intersected cross-sections with high-precision interpretation, the 3D model cannot reflect all details of the sections for long gaps between consecutive

Table 3
Quantity comparison of assessment cells of each grade without strata constraints.

Quality grade	5 s × 5 s		10 s × 10 s		20 s × 20 s	
	Cell number	Proportion (%)	Cell number	Proportion (%)	Cell number	Proportion (%)
I	2559	0.30	668	0.48	139	1.41
II	6268	10.14	1502	7.35	445	8.79
III	13169	48.93	3278	47.11	855	46.97
IV	14836	30.68	3728	34.39	991	31.92

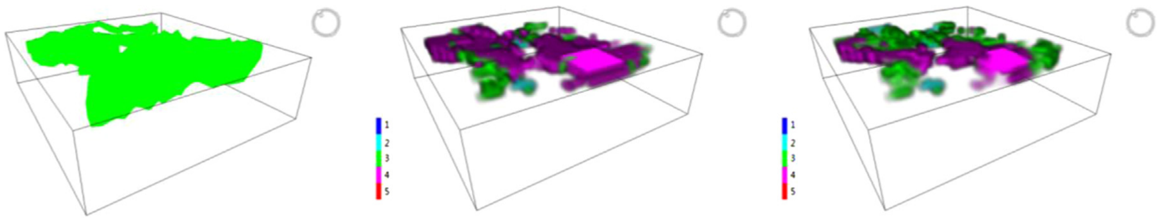

Fig. 7. Quality assessment results with the constraint of the volume of Wanqinsha section. Left is the distribution of Wanqinsha section, the middle is the assessment result without strata constraints, and the right is the assessment result with strata constraints. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 4
Assessment results comparison of Wanqinsha member area.

Quality grade	Without stratum constraint		With stratum constraint	
	Cell number	Proportion (%)	Cell number	Proportion (%)
II	18	0.12	24	0.16
III	177	1.179	404	2.69
IV	628	4.182	395	2.631

cross-sections. Therefore, in one geological block, several boreholes might be enclosed. However, the interpolation process in the block was not decided by the sample point and its related attributes rather than the stratigraphy of the block. Thus, the precision of the 3D geological model affects the interior evaluation. Also, it affected the boundaries and distribution of quality levels.

Furthermore, the cell size is anther vital factor in this process. As mentioned above, one of the key steps is to partition the underground space area spatially, because the basic size eventually impacts the accuracy of the UUS quality estimate. The results illustrated that their volume and spatial distribution varied significantly at different scales. Although the uncertainties caused by cell scale and geological attributes were separately discussed in this paper, in fact, these two factors are correlated. The change of basic cell for estimation impacts the geological attributes' values, which also alters the spatial distribution of the estimation results. If the cell size is bigger than the geological block, the constraints of geological block are valid.

4.3. *Pondering on the indices and related weight values*

For this study, an index system was constructed for the geological features because we were only concerned with the quality of the UUS natural resources. Hydrological conditions, such as depth of groundwater table, the corrosive potential and possible groundwater, were not treated as a part of the index system for the lack of data. However, this omission does not affect the effectiveness of the method, although it will affect the final result. In the method presented, new factors can be easily inserted into the assessment flow. The weight values of the subject layers were given by experts because the geological condition is different in the different areas and this situation should be judged by geologists and other experts. Nevertheless, the weight values of the factors such as density and modulus of compression were calculated by an objective method, which can reveal the relationships among them.

5. Conclusions

The quality assessment of UUS is a comprehensive process and involves many influencing factors that interact with each other. Understanding the importance of every factor and classifying the level of those factors are one of the key points in the evaluation process. The other key point is limitation of sparse data and knowledge about the geological features. In the case of the city of Foshan, we presented a method to evaluate the quality of urban underground space resources based on the VFS theory. Some researchers have proved that the VFS method is to be reliable for that kind of assessment (Guo and Chen, 2006; Jiang et al., 2007; Li et al., 2012. In this study, we used the method presented by Jiang et al. (2007) and did not modify or change the basic process. The biggest difference between the method in this study and that of Jiang et al. (2007) is that a 3D geological model was introduced into the evaluation process as a constraint in extracting factors' values. Coupling with a digital geological database and a 3D geological structure model of the study area, this research constructed an evaluation system based on an index, and explored an attribute extraction method within the constraints of a 3D geological model.

From Table 3, we noticed that the volume of Level 3 and Level 4 occupies the most area of this study area. This means that the UUS in this study area is fit for development. Although the scale can affect the final result, it cannot change general distribution status. Table 4 shows different final results by the percentage of every quality level of one geological body, and it described the effect of stratum constraints in the assessment. The cell number of every quality level changed largely because the attribute's interpolation is limited by the body boundary. This may shield the effect of those samples outside of the geological body. That means the constraints of the 3D geological model affect the final results. On the comparison of evaluation results with unit scale and strata constraints on interpolation, this study revealed that the final evaluation result is affected by cell size and geological model constraints simultaneously. The 3D geological model has a major influence on the shape of quality levels and their distribution. For the Wanqinsha member in the study area, variance in the numbers of cells and variance in different quality grades illustrated that the strata constraints impacted the final assessment results significantly. Therefore, to get an accurate result, we need to choose the cell size carefully according to the average sampling distance of the borehole samples.

This study made an attempt to introduce the 3D geological structural model into the case of quality assessment of the UUS and more work is needed to be carried out. Several aspects of this research are to be developed further including investigating the results in other cases. Additional impacts on the analysis of each factor on the final result should also be investigated in the future.

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