

# Application of 3D GIS to 3D Cadastre in Urban Environment

Shen YING, Renzhong GUO, Lin LI and Biao HE, China

**Key words:** 3D Cadastre, 3D GIS, Visualization, Data model, Decision-making support

## SUMMARY

Rapid development has promoted the 3D land use in the urban environment with the increasing requirements of the complex interweaving, such as dwellings, commercial areas, public transportation and urban utilities and infrastructure. 3D cadastral objects are features which concern urban planning, land resource and real estate of municipalities, whether they are on, above or below the earth's surface. In essence, the 3D cadastral objects are content and partition of urban geographic space, and they aim at registering legal status and property rights associated with land and other real estates or properties (Guo, Ying, 2010). It has become a huge challenge for governments to manage 3D land space breaking through the traditional 2D information system, which needs the support of 3D techniques.

At the same time, 3D techniques in 3D GIS, including 3D data collection, 3D data model, 3D data management and visualization, have been applied in fields such as urban planning and virtual city. This provides a suitable background and base for developing 3D cadastral systems. Also 3D GIS offers proper methods to represent the geometry of 3D cadastral objects and to associate the property rights, semantics and transaction attributes to them. Can these techniques be directly introduced into 3D cadastral systems? Some techniques can be directly applied in 3D cadastre, while others should be further improved and adapted to cater to the field of management in 3D land administration because of the difference of the objects between 3D GIS and 3D cadastre. There is a broad potential field where 3D GIS should be deeply studied, such as valid 3D geometric primitives, 3D integrated visualization of entities on, above and underneath the earth's surface, as well as 3D spatial analysis.

This paper aims to apply 3D GIS techniques to 3D cadastre in urban environment to bridge the gap between urban simulation and urban space management system. This paper will elaborate the details of the applications of 3D GIS to 3D cadastre from three aspects: 3D data and 3D modeling, 3D simulation and visualization, practice and decision-making support.

Cadastre is a combined feature that includes the natural entity, person and party, as well as government and its authorization. Therefore, each 3D cadastral object becomes a behavior-aware 3D model because of human actions involved within the space of 3D cadastre. Moreover, the management of 3D cadastral objects leads to a geometry-aware cadastral model because there may be coincidences with other cadastral objects like a neighbors. This integrates the natural features with human beings, and promotes the harmony between people and society.

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## 1. INTRODUCTION

Rapid development has promoted the 3D land use in the urban environment with the increasing requirements of the complex interweaving, such as dwellings, commercial area, public transportation and urban utilities and infrastructure. Figure 1 shows the complex building of Wanxiangcheng in Shenzhen constituted by one commercial center, one skyscraper and one overcrossing building that covered two land parcels and a public road. 3D cadastral object are features which concern urban planning, land resource and real estate of municipalities, whether they are on, above or below the earth's surface. In essence, the 3D cadastral objects are the content and partition of urban geographic space, and they aim at registering legal status and property rights associated with land and other real estates or properties (Guo, Ying, 2010). It has become a huge challenge for governments to manage 3D land space breaking through the traditional 2D information system, which attracts world-wide focus and research (Van Oosterom, Stoter, Ploeger, et al., 2011). An international 3D Cadastral Working Group had been set up by the FIG (International Federation of Surveyors) from 2001 to innovate and promote the development of 3D cadastre.



Figure 1. Photo of Wanxiangchen

In China, Property Law had been enacted to support the 3D confirmation of the cadastral objects regardless if they are above, on or under the earth's surface, which provide the legal foundation to establish the 3D cadastral system. To define the 3D cadastral object, represent its 3D space and associate it with its attributes and rights become the key contents for the 3D cadastral system.

New challenges are encountered for 3D cadastre to represent and manage the 3D geometries of cadastral objects, handle spatial relationships among them, visualize them, and more complicated, manage them with spatial-temporal relationships along with parties as well as rights, restrictions and responsibilities. At the same time, the geospatial and engineering industries, especially 3D GIS (Geographic Information System), have been evolved a very quickly. 3D GIS offers proper methods to represent the geometry of 3D cadastral objects and to associate the property rights, semantics and transaction attributes to them. This paper aims to apply 3D GIS techniques for 3D cadastre in an urban environment to bridge the gap between urban simulation and urban space management system.

Goodchild (2010) proposed the question: “What use cases exist for 3D data and 4D data? ... For example, is a building better modeled as a set of walls in 3D, or as a linear network of nodes (rooms) and links (doorways, hallways) embedded in 3D? What are the primitive elements of a GIS representation of a building, and what is the relationship between architectural design (e.g., planar walls, rectilinear corners) and GIS representation?” Here, 3D cadastre/4D cadastre is a classic case for 3D data and 4D data, and a 3D property unit is a basic element in a 3D city urban management system. Also a 3D property unit is a comprehensive concept that integrates lands, houses or other real estates with 3D data, parties and human behaviors.

However, some of the issues are more or less solved in 3D GIS, such as 3D modeling, construction of 3D primitives and simulations, which provides a suitable background and base for developing 3D cadastral systems. But, at the same time, they lay particular emphasis on different aspects. Some techniques in 3D GIS can be directly applied in 3D cadastre, while others should be developed further or adapted to comply with the field of management in 3D land administration. 3D GIS software like Oracle and Microstation were investigated by Zlatanova et al. (2002). A similar topic based on Bentley Geospatial software was discussed by Frédéricque et al. (2011). An overview of the utilization of 3D GIS to model, manage and visualize 3D cadastral objects, as well as to support decisions support based on our on-going project, is presented in this paper. With 3D GIS applying to 3D cadastre, the following technical problems need to be solved:

- What is 3D space in 3D cadastre and what is the particularity of 3D space for 3D cadastre?
- Can 3D data collection in 3D GIS also be used in 3D cadastre?
- Are there any special requirements in 3D modeling and management in 3D cadastre?
- What's the difference between visualization in 3D GIS and in 3D cadastre?
- What kind of decision-making support can be provided with 3D GIS for 3D cadastre?
- Can 3D WebGIS be suitable for dissemination and publish of 3D cadastral information?

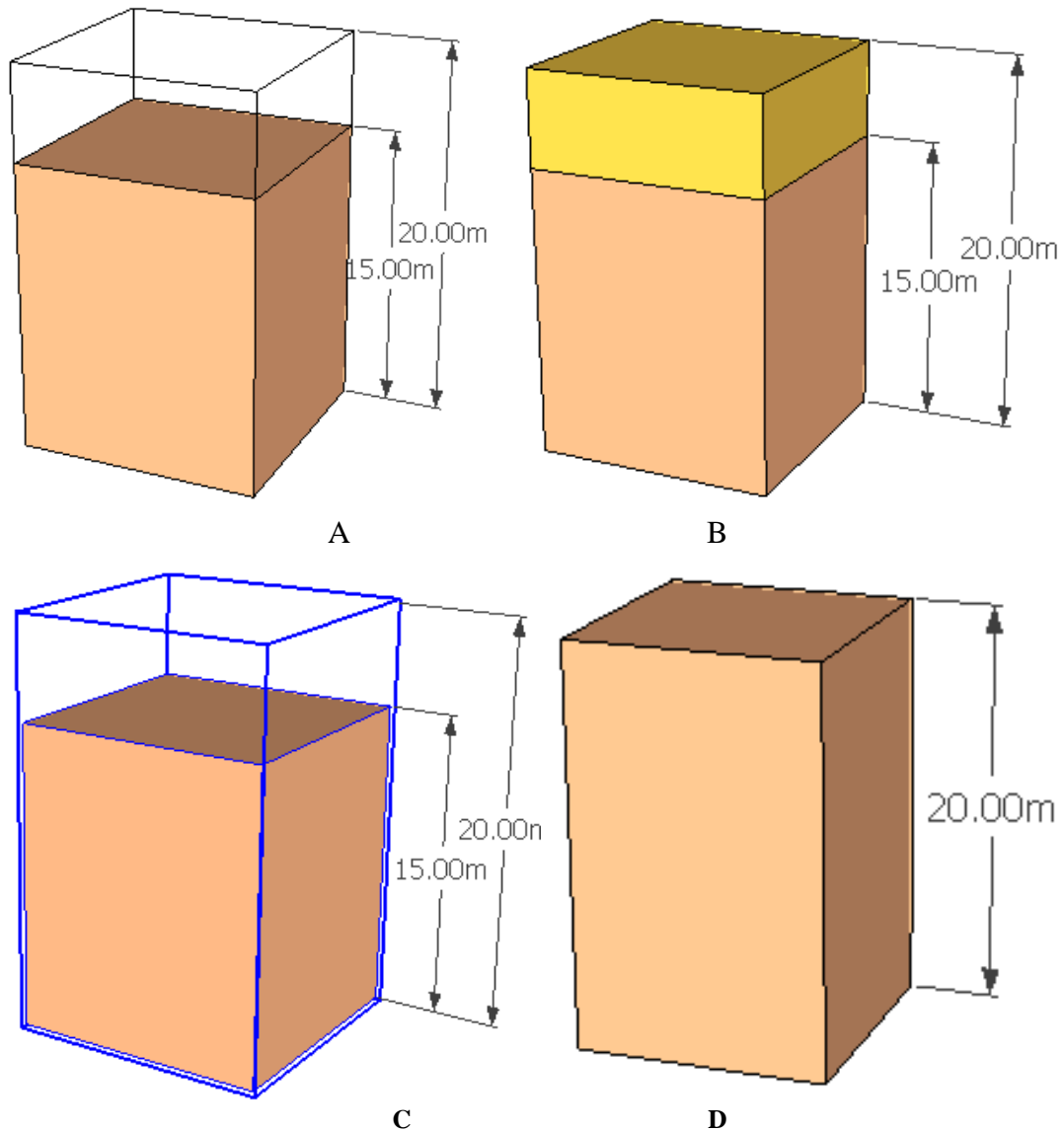
The paper is organized as follows. After the introduction, basic discussions about 3D cadastre and 3D space are expressed in section 2. 3D data generation and 3D modeling are addressed in section 3. Section 4 discusses the visualization techniques for 3D cadaster. Decision-making support and dissemination of 3D cadastral objects for practical applications are elaborated in Section 5, with the following concluding remarks in Section 6.

## 2. 3D CADASTRE AND 3D GEOSPACE

Although registration and rights are the essential elements in land administration systems, the core element that they are imposed on is the land parcel, with its 3D land space or 3D geospace. 3D cadastre is a discrete division of 3D urban geospace, and many urban features, such as buildings, parks, tunnels/metro, underground constructions, overcrossing buildings, are the 3D cadastral entities. From the perspective of space, land, buildings and all the other entities are coherent for 3D cadastre. The rights, restrictions and responsibilities that people own and undertake associated with these entities are equal to that associated with the corresponding geospace of these entities. So land and other real estates or properties are consistent in the aspect of geospace, and 3D geospace management provides a uniform framework for 3D cadastre. All the 3D cadastral objects can be located unambiguously with geo-referenced coordinates, and occupy an exclusive volume of geospace. These occupations of geospace are the kernel and the essence of 3D cadastral objects. Through their management, the 3D cadastre upgrades and transcends the existing management system of land and real estates.

3D cadastral space unifies the physical construction space with the legal space. Although a 3D cadastral object occupies some geospace, its geospace may not be fully filled by physical entities. For example, one cadastral space (Figure 2A) is  $10 \times 8 \times 20\text{m}$ , and the construction space is  $10 \times 8 \times 15\text{m}$ , how to represent these phenomena? There are two ways to represent them. First, the difference between the physical space and the “air” space is drawn in different ways, and the “air” space is depicted with wire frame or different colors to show its difference with physical space (Figure 2A and Figure 2B). Notably, these two types of space are inseparable and there is only an integral space including both of them (Figure 2C). Another way is to show the holistic legal space regardless of the physical space. Since the 3D geographic space (geospace) is homogenous in legal aspects within one 3D cadastral object, there is no difference between the physical and “air” space, and they can be modeled and visualized in a unified way (Figure 2D). In a full 3D cadastre, a volumetric parcel is not necessarily visible in reality and only indirectly related to physical objects (Döner, Thompson, Stoter, et.al., 2011).

Next, we will elaborate the details of the applications of 3D GIS for 3D cadastre from three aspects: 3D data and 3D modeling, 3D simulation and visualization, practice and decision-making support.

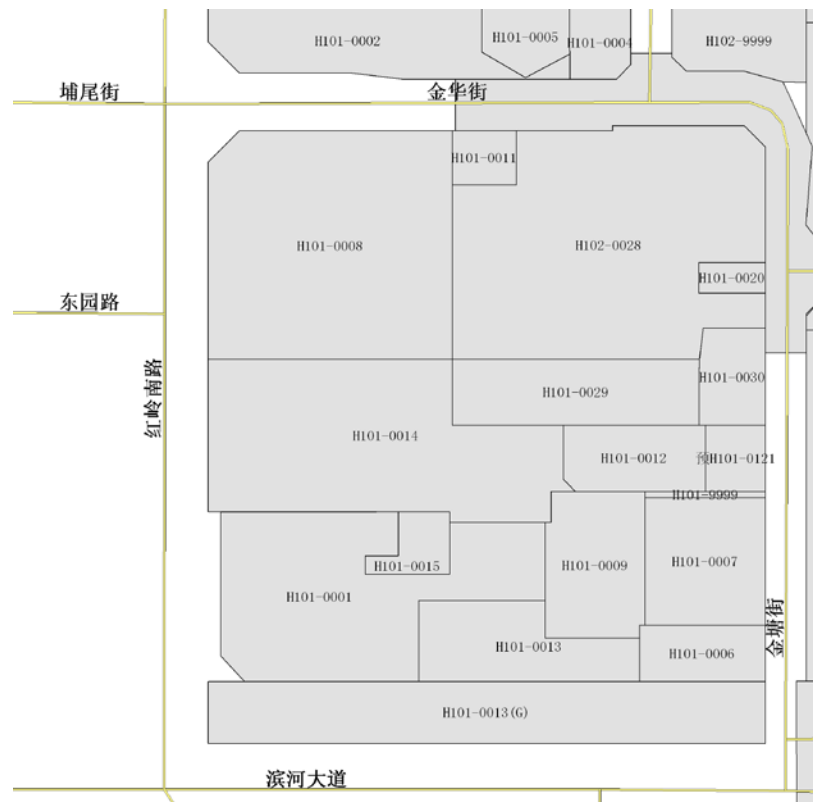


**Figure 2. 3D space: A) physical and air space with solid and blank/wireframe representation; B) physical and air space with different colors; C) inseparable cadastral space; D) unified representation**

### 3. 3D DATA AND 3D MODELLING

First of all, geospatial modeling is the foundation for both GIS and cadastral systems. Comparing to the general modeling of common geographic features, such as road, block and building, 3D cadastral systems focus on creating 3D models of all cadastral objects, including 3D land parcels, 3D buildings, 3D property units and their collection. The particularity of each cadastral object is that it's a geometric 3D primitive, which is a closed space that can be represented by a solid or a closed polyhedron. Also the 3D boundary of the cadastral objects should be accurate.

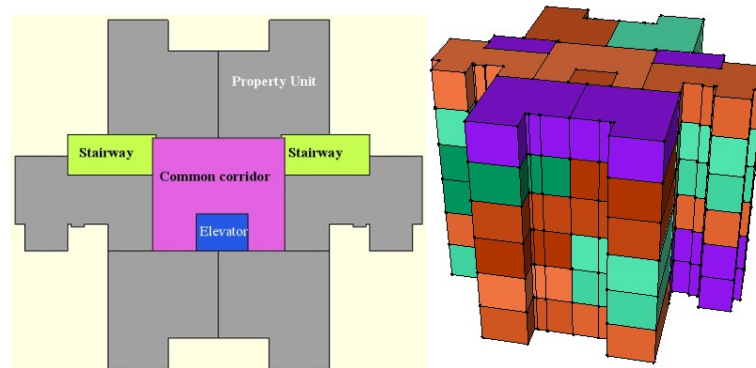
Officially, the cadastral data are derived by certain people and sections in the municipality. Generally the geometries are surveyed and mapped by surveyors, and rights and semantics are authorized by specific laws and regulations, contracts and governments. From the perspective of geometry, there are already 2D boundary points, lines and faces (as Figure 3 shows), sometimes with 3D coordinates. It is evident that a 2D cadastral map cannot describe the 3D space and their relationships. 3D geometric representation is necessary to delimit the 3D space that the owner possesses with certain rights and responsibilities. This raises the technical problem how to construct valid 3D primitive to represent a 3D cadastral object.



**Figure 3. Traditional 2D parcel map**

3D GIS techniques including 3D data capturing based on 3D laser scans or images can provide certain 3D data, but these 3D data mainly concern physical shapes and are not feasible for 3D cadastral context. There are three ways to build 3D geometric primitives for 3D cadastre. Firstly, extruding the existing 2D footprint or blueprint to get a 3D outer boundary (Ying, Li, Guo, 2011; Ledoux and Meijers, 2011). Generally from the resulting shape valid corresponding 3D solids can be constructed (Figure 4). During this process, the plans of the building or proposed buildings should be available (Figure 4A), and the elevation and height should be known ahead of the extrusion. Secondly, a straightforward approach is to straightforward detect and recognize the valid 3D solids from the given 3D boundary facets. This processing needs a strict algorithm with the support of proper geometry and topology (Ying, Guo, Van Oosterom, et al., 2011). Last but not least, 3D cadastral models can be imported from 3D Building Information Models (BIM) or CityGML. But the difference between them and the cadastre should be kept clear in mind because in the difference of the definitions about the elementary features. For example, only the outer boundary of the property unit is needed in

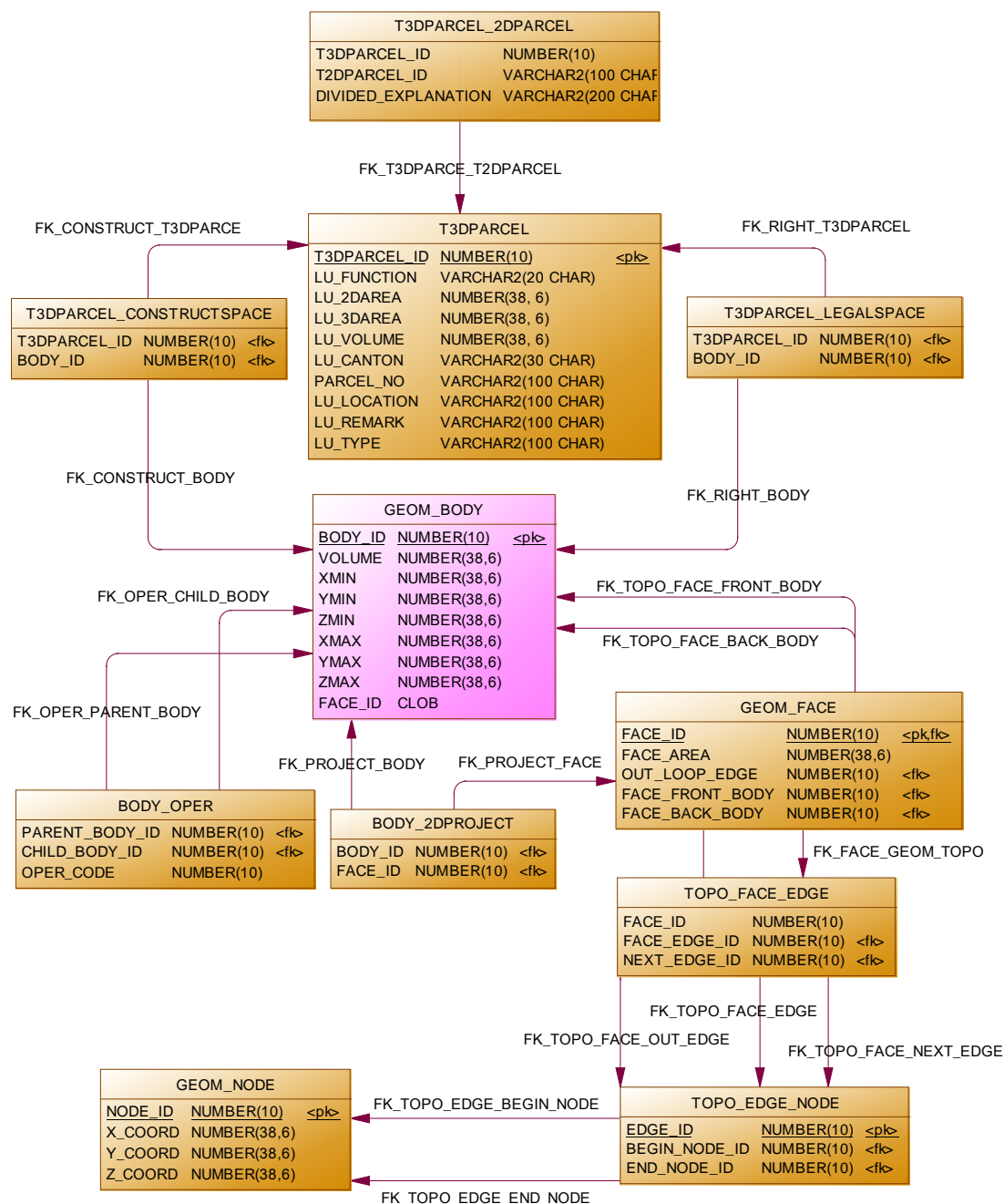
cadastre, but detailed geometries of roofs, rooms and even indoor furniture are also provided in CityGML LOD2/LOD3 or BIM. Also the geometric location is a little different because there is thickness information on BIM or walls in CityGML, but cadastre only pay attention to the linear legal boundaries without thickness that may be depicted by physical walls.



**Figure 4. Extrusion from plans: A) plans of the legal boundaries of the property units; B) Collection of the 3D property units**

During the modeling of 3D cadastral objects, more attention has to be paid on the validation of 3D models, especially for sets of property units that need consistent and precise geometric as well as topological relationships among 3D cadastral objects (Ying, Guo, Van Oosterom, et al., 2011; Thompson and Van Oosterom, 2011). Each 3D volume cadastral object has a closed 3D space represented by 3D geometry, which needs effective methods to validate its closeness and interior connectivity. Many solid modeling tools put up the discrete faces together without inherent 3D structure to represent 3D geometries. Direct construction of valid solids from discrete faces and real 3D geometry can provide an efficient approach to model 3D cadastral objects (Ying, Guo, Van Oosterom, et al., 2011).

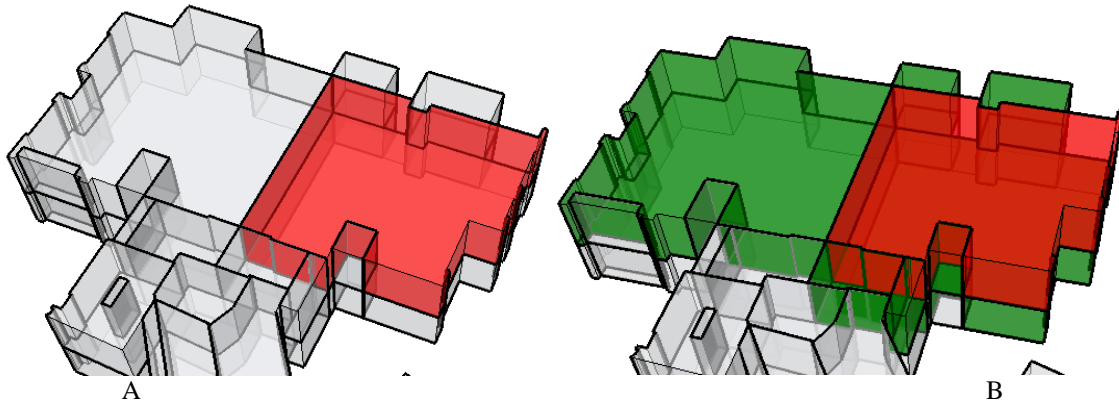
A 3D GIS provides a certain spatial database to manage 3D cadastral objects, which enhance the level of the 3D information management and improve the efficiency. Updating and maintenance of the 3D cadastral objects is also necessary. The real 3D geometric primitive “3D BODY” is defined, and also two feature classes (3D land/legal space and 3D construction/building space) that are inherited from class “3D Parcel” are defined and associated with the geometric 3D BODY. The topological elements are hierarchically interrelated, and (n-1)-dimensional geometric primitives are used as boundary of n-dimensional geometric primitives. All the objects can be directly stored in an Oracle database with its own structure. Database schema of our 3D cadastral project is expressed in Figure 5, moreover, detailed relationships and links among the different geometric primitives and cadastral objects are depicted in the diagram, as well as class definitions of the attributes of each class.



**Figure 5. Database schema in Oracle**

As 3D models and topological relationships are stored in Oracle, spatial query can easily be implemented. The results of a topological query show the selected 3D property unit with its shared common faces (Figure 6).





**Figure 6. Topological query based on 3D models**

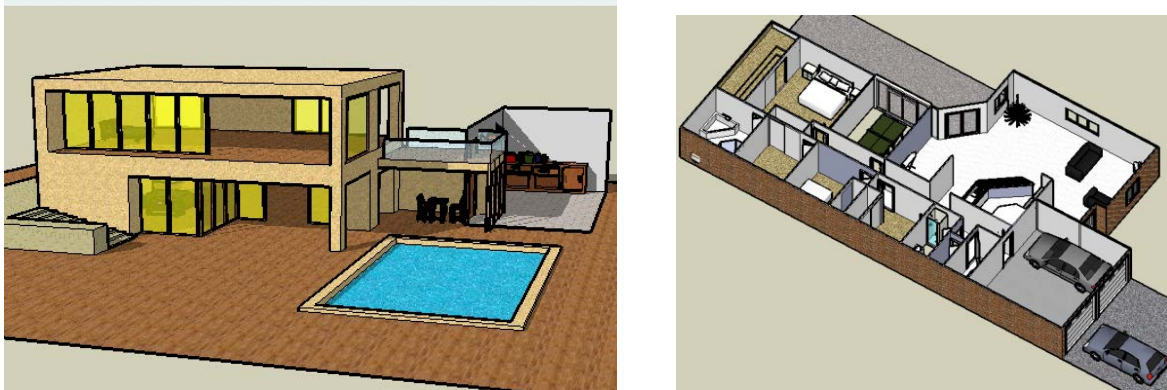
#### 4. VISUALIZATION

It is not easy to use traditional visualization technologies of 2D maps, such as diagrams, To paint or depict 3D cadastral objects as colorful blocks. Without visualization of 3D objects, 3D property can not be represented in the so called 3D cadastral map which shows the location of objects and properties in space. The visual obstacles of physical entities or nest relations among different geospaces result visualization in difficulties. The aim of visualization is to show the location, as well as the context of 3D cadastral objects and highlight them. This section will describe the technologies facilitating visualization of the distinct locational relationships of 3D cadastral objects.

In terms of visualization, there are many differences between 3D cadastre and virtual city/architecture, and emphasis is shifted from urban simulation to the distribution of 3D land space, 3D property units and other cadastral objects. Visualization for architecture focuses either on the holistic view and harmonic fusion of the architectures and the surrounding environments (Figure 7), or on the functional division or the configurations of the interior of the architectures (Figure 8). The visualization for architectures emphasizes the reality of architectural entities and their functions, and stresses the visual effects of the exterior surface or interior construction. Objects for architecture visualization are walls, doors, windows and so on. Other visualizations, such as urban simulation and virtual city, focus on visual simulation of the exterior “skin” of the city. They pay more attention to the facade surfaces of the models and to photo textures for photorealistic looks, not to the interior “units” under the skin (Figure 9).



**Figure 7. Visualization of architecture**



**Figure 8. Visualization of interior division of the architecture**



**Figure 9. Landscape design and city simulation**

However for 3D cadastre, the kernel is to describe the precise boundary of property units (see Figure 6), and cadastral objects focus on the geospace under the cadastral rights, despite the fact that this geospace may be delimited by the physical walls of architectural properties. The visualizations of 3D adastre illustrate the distribution of occupation and partition of land space and urban space in order to give clear ideas for users or to support decision-making for the government.

The core unit for a cadastral object is its 3D geometry as well as its corresponding RRRs and parts. According to the relationships between the boundaries and physical entities, there are two types of 3D cadastral objects: physical objects and non-construction-based cadastral objects. The geometric boundaries of the 3D cadastral objects are the statutable or legal geographic surfaces, which can be part of realistic/physical entities or can even be legal “blank” or “virtual” surfaces. Accurate three dimensional descriptions of cadastre and property become an important need of governmental management and citizens’ rights. Taking the Shenzhen Bay Port as an example of a non-construction-based object, the Hong Kong Port Area in the Shenzhen Bay Port is a special spatial box that they Shenzhen Government leases to the Hong Kong Government, both customs are located in one building. The building is 30-meter high (Figure 10 A), but the 3D cadastral space for the Hong Kong Port Area at the Shenzhen Bay Port is from -60 meters to +60 meters and includes much more “air” space and parts of the building (Figure 10 B).Ror details see Guo et al. (2011).

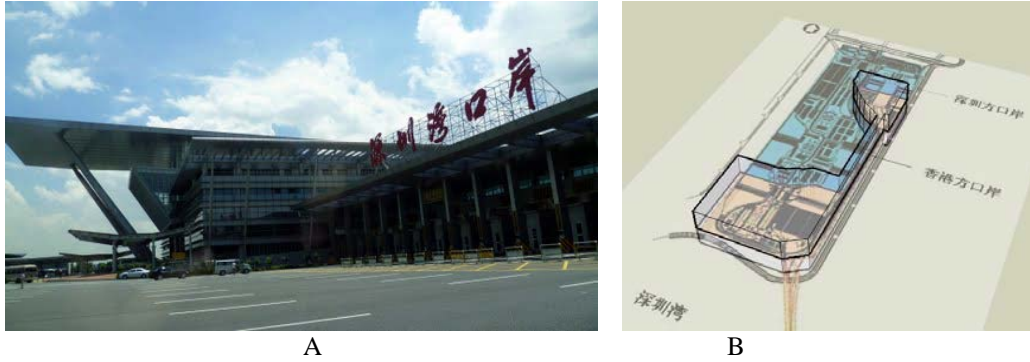
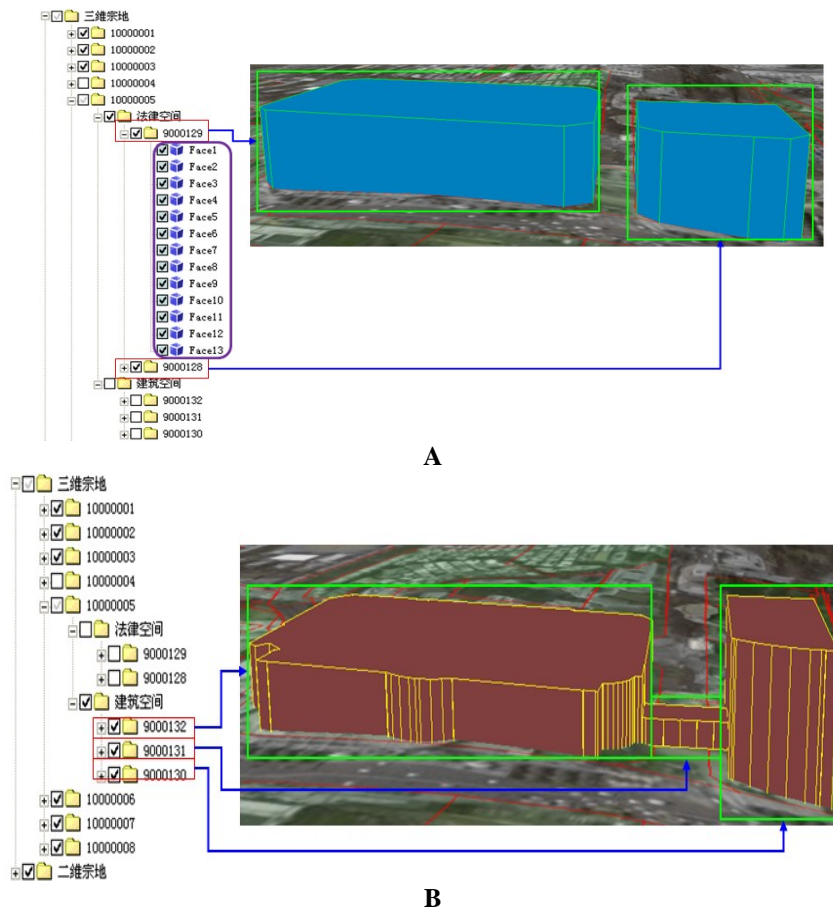
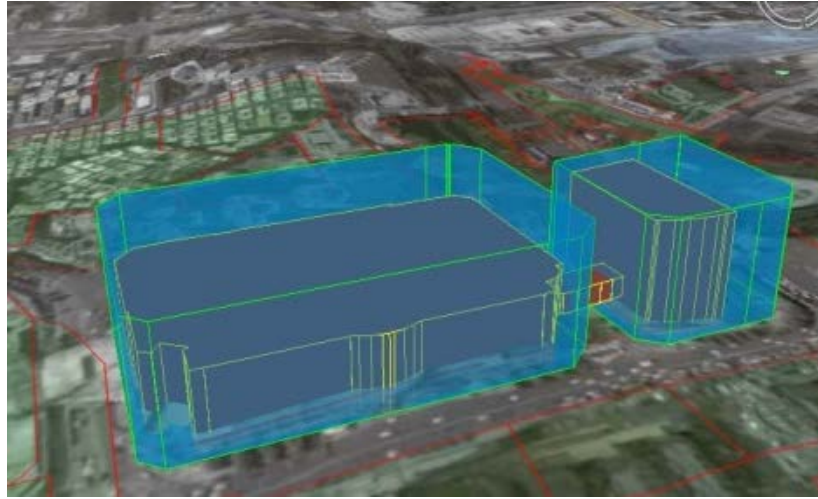


Figure 10. Non-construction-based 3D cadastral object: A) building; B) 3D space of cadastral object

Because of the deep influence of the traditional 2D cadastre and the objective of the division of land and housing in a municipality, we design two types of cadastral geospace: 3D land space and 3D housing/building space. 3D land space is a certain vertical extension of the 2D parcel according to plannings or demands of architecture, and 3D housing/building space is the physical space or its approximation. Normally 3D land space contains the corresponding 3D housing space. But for an independent 3D cadastral object, its 3D space may have no relation with its corresponding vertical surface parcel. Figure 11 describes the face organization of 3D land space and 3D building space, and the corresponding visualization.



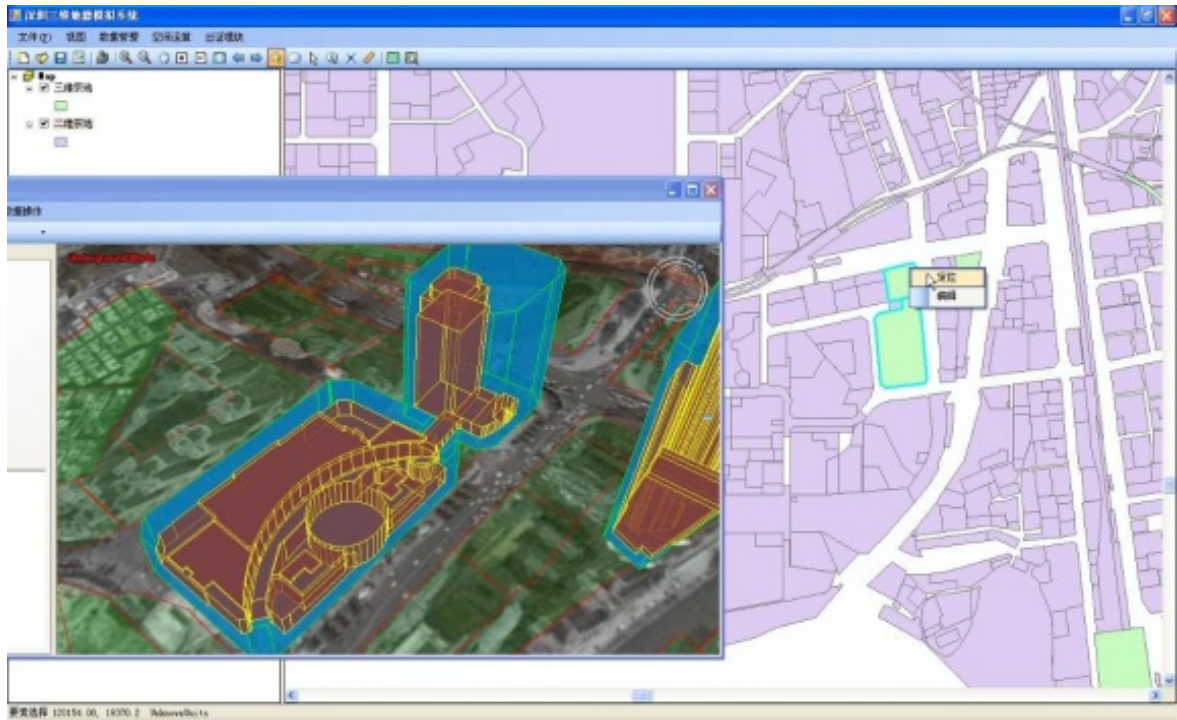


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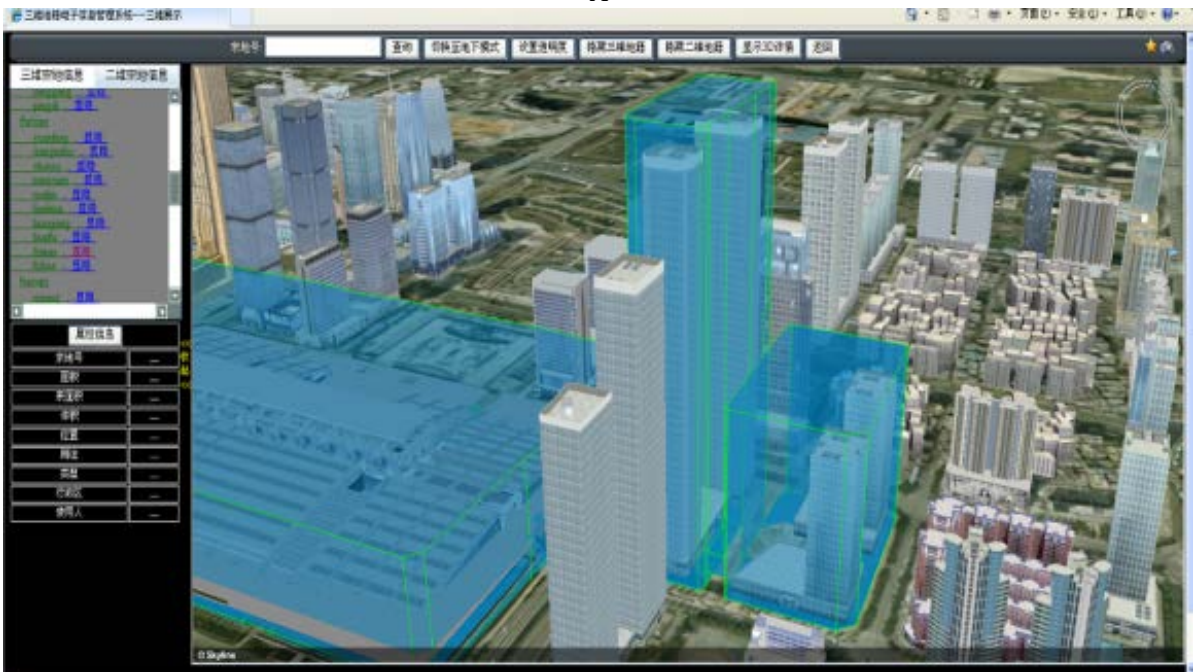
**Figure 11. Organization of the geometric data and visualization about 3D land space and 3D building space: A) 3D land space; B) 3D building space; C) visualization**

Since the geospace of 3D cadastral objects mainly embody in two aspects - 3D land space and 3D property space - to create a 3D cadastral map is the best way to visualize them and to illustrate their locations and 3D geospaces. To depict the different cadastral spaces simultaneously we need to use some techniques to deal with the difficulties to show them correctly and visualize the locational relationship between them. Alternatively, in-line interactive visualization between 2D and 3D are introduced, as Figure 12A shows. The footprint of the 3D land space is highlighted in the 2D parcel map. Additionally the 3D land space and the 3D buildings space are drawn at the same time with a floating pop-up window. The 3D land space and the 3D buildings are portrayed with photographic textures as well (see Figure 12B). To show the difference and the nested relationship between the 3D land space and the 3D buildings, transparency technique is used for 3D land space to show its interior 3D buildings. Through these techniques of visualization the spatial divisions, locations and the context of 3D cadastral objects can be interpreted by the users clearly and intuitively.

Additionally the underground model and digging a hole on surface can be used to visualize the shapes of 3D cadastral objects beneath the earth's surface (Figure 13).

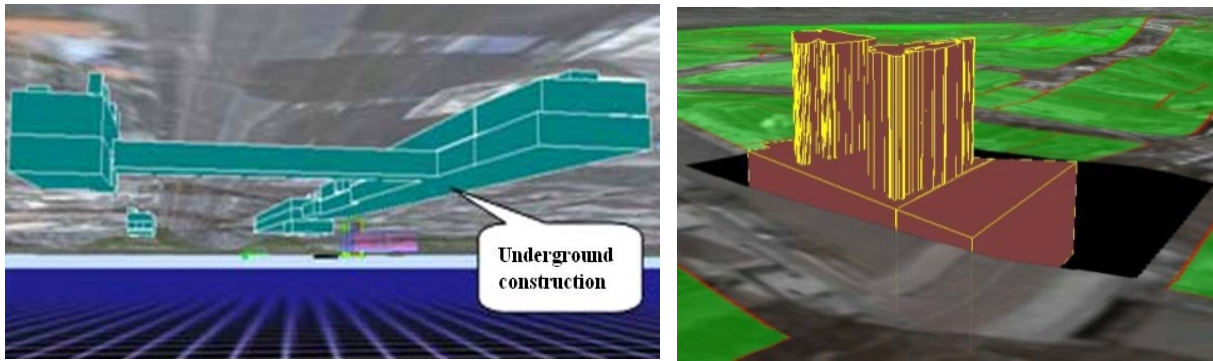


A



B

Figure 12. Visualizations of 3D land space and 3D buildings: A) in-line visualization between 2D and 3D scenarios; B) visualization of 3D land space and 3D buildings

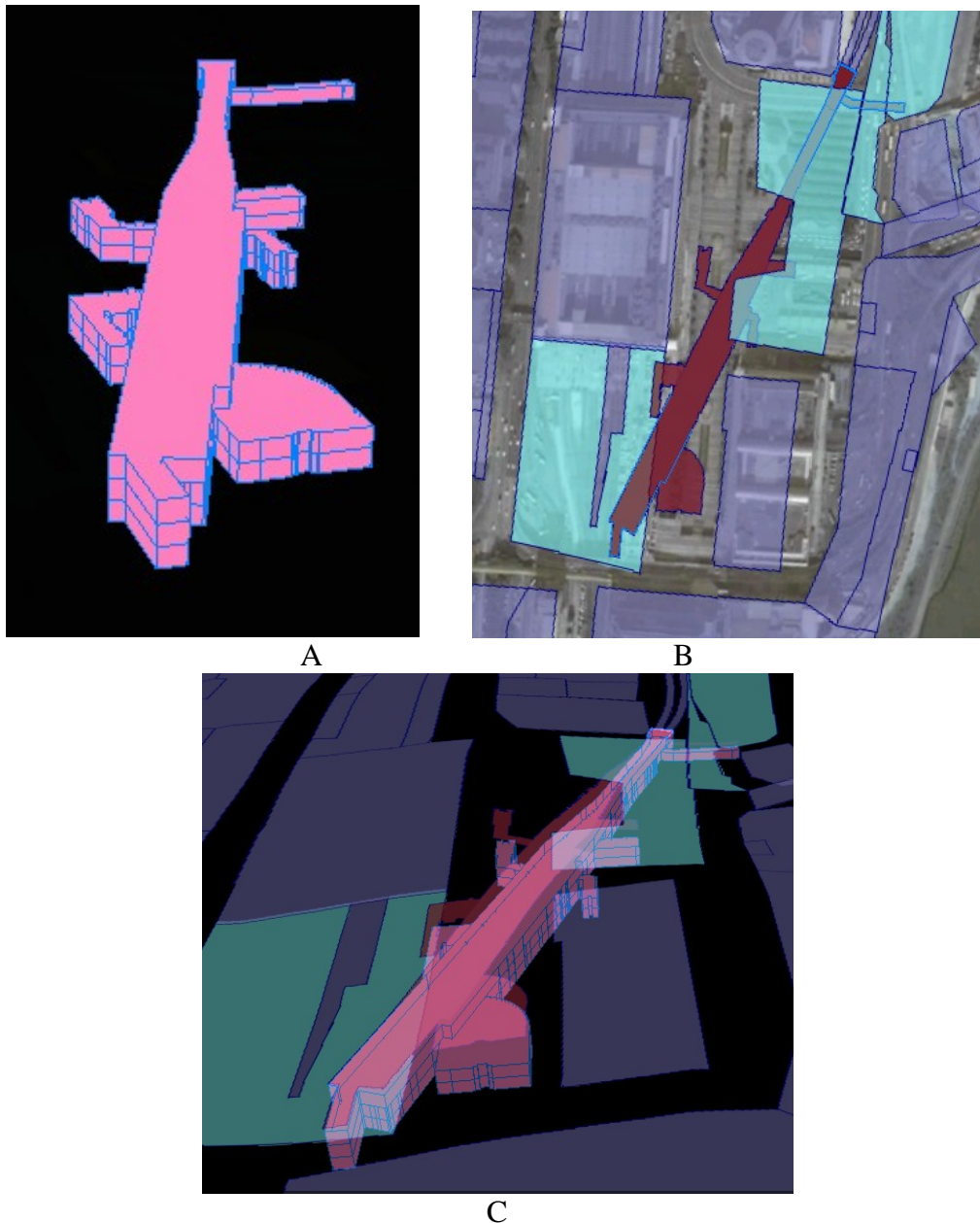


**Figure 13. Visualization of 3D cadastral objects with underground model and digging a hole**

## **5. APPLICATION AND PRACTICE**

Most 3D GIS techniques can be utilized in various applications, such as urban planning and architecture design. But as for 3D Cadastre, 3D GIS still have a large potential market for the implementation of 3D land use management, not only because of the particularity of intrinsic 3D cadastral objects, but also because of the 3D techniques that are needed for 3D land decision-making.

Most important things about 3D cadastre for government is their management and decision-making support. Although traditional aspects, including location distribution, statistical analysis and history storage and trace, still play a backbone role in cadastral system, the municipality wants the management and application of a 3D cadastral system in urban space to plan and make decisions for future urban space. For example, metro planning in 3D should take into consideration the surface parcels and the underground basements of all the constructions the metro route passes by, and this needs support by functions like 3D buffer analysis and 3D conflict detection of spatial overlays. The vertical projection plan of an underground 3-floor metro Station (Figure 14A) intersects with several surface parcels (Figure 14B) that overlay the metro and its passageways, A 3D view of all the involved objects in Figure 14C. At the moment 3D primitives allow volume calculation which implicates new methods for tax and plot ratio.



**Figure 14. 3D planning of metro station: A) 3-floor metro station; B) projection plan of metro station (red) intersecting with surface parcels (blue); C) 3D view of all the involved objects**

With the development and implementation of our 3D cadastral project, practical applications are carried out in Shenzhen (Urban Planning, Land and Resources Commission of Shenzhen Municipality). Their Office Automation System has been integrated with 3D cadastral systems, such as 3D land planning, 3D land for bidding and sale, as well as 3D registration and 3D certifications. A real 3D slot of an underground parking for auction<sup>1</sup>, whose 2D projection overlays two surface parcels and a public road, is illustrated in Figure 15.

<sup>1</sup> <http://www.szpl.gov.cn/tdzpg/land.aspx?exchangeid=20110406001>

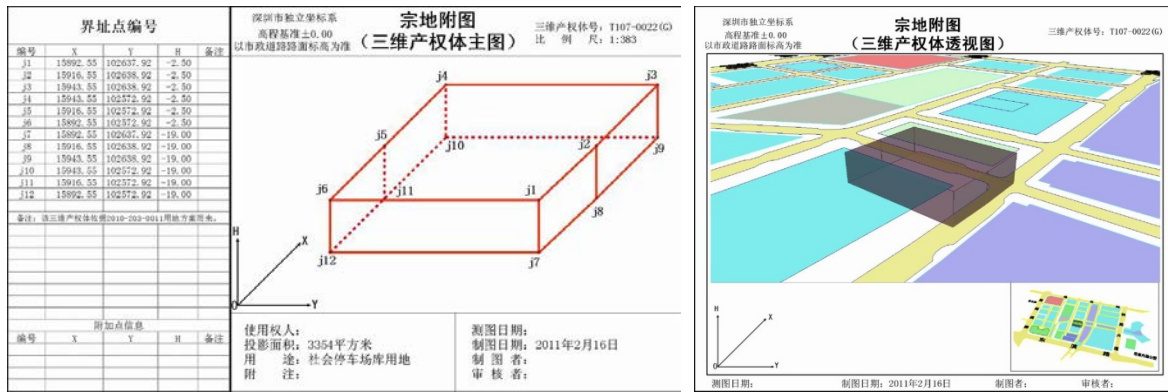


Figure 15. A real underground 3D parking slot for auction

The application and practice of 3D cadaster in the Shenzhen office automation system is built on B/S architecture (Figure 16), and can be used by all employees within the Commission whose departments are spread across more than ten places all over the Shenzhen Administrative Zone. The system supports the full 3D cadastre, integrated with the existing 2D cadastre. In this architecture Flash and TerraExplorer Viewer together with our own programs and developments are embedded in the IE (internet Explorer) browser. So 2D and 3D cadastral data from an Oracle database can be browsed. On the server side, TerraGate provides a 3D terrain service, and other 2D or 3D data associated with the spatial attributes are stored in an Oracle database because of its very large volume. The client user can retrieve the 2D geographic information data (including 2D parcels) via ArcGIS server and 3D cadastral information through WMS (Web Map Service) and WFS (Web Feature Service) within SFS (Spatial Framework Service). The main page for the client user expresses basic 2D parcel, 3D space with image and basic attributes, as Figure 17 describes. The 3D views of 3D cadastral objects are similar to Figure 12.

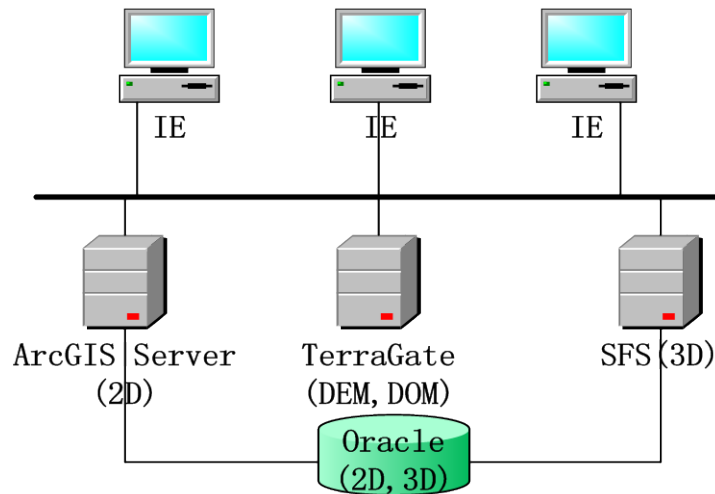


Figure 16. Web-based 3D cadastral system



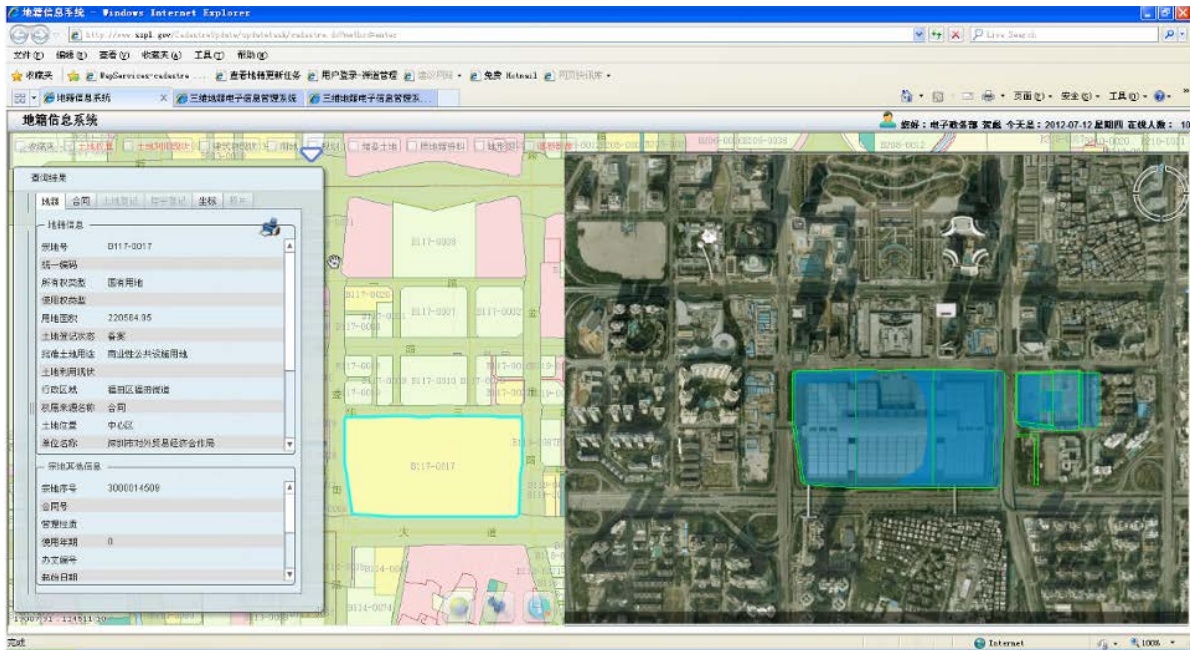


Figure 17. 3D cadaster system based on B/S architecture

## 6. DISCUSSION AND CONCLUSION

Cadastral is a combined feature in reality, because it includes the natural entity, person and party, government and its authorization, as well as rights, responsibilities and restriction. Therefore, each 3D cadastral object becomes a behavior-aware 3D model because human actions are involved within the space of 3D cadastre. Moreover, through the management of 3D cadastral objects the cadastral model becomes geometry-aware because there may be coincidences with other cadastral objects like neighbors. The establishment of 3D cadastre can clarify the 3D property space for citizens, and decrease the debates and disputes about property right. This integrates natural features with human beings, and promote the harmony of the society.

3D description and management of property units strengthens the management of government objectively, and potentially reduces disputes or arguing about property units and land space, which has significant social benefits. The paper describes the integration with 3D GIS in several aspects, including data modeling, visualization and practical applications. Many technical problems still need more research, and more prototype systems and application demonstration projects are ongoing in Shenzhen. It is still a long way to completely implement 3D cadastre, not only the technical problems, but also the legal and administrative issues.

## ACKNOWLEDGMENT

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