Research on voxel-based land complex modelling and adaptive resolution expression methodology

Di Sun[1], Tao Shen[1], Liang Huo[1], Fulu Kong[1]

[1] School of Geomatics and Urban Spatial Informatics, Beijing University of Civil Engineering and Architecture, Beijing 100044, China; sundi0204@163.com

Keywords: Voxel Model, Land Complex, Voxel Modelling, Dynamic Representation, Adaptive Resolution.

Abstract

In order to improve the efficient use of land complex resources, explore the application of voxel model in land complex change monitoring, and propose a voxel-based land complex modelling and adaptive resolution expression method for the problem of large data redundancy and poor expression effect in the dynamic expression of land complex voxel model.Firstly, voxel classification and stratification are carried out through element characteristics to determine the elements suitable for voxel modelling; then, based on the analysis of terrain factors, the adaptive resolution expression method is constructed by optimizing the node evaluation criterion through the comprehensive consideration of sight distance and comprehensive terrain complexity.The results show that the method in this paper can achieve efficient expression and smooth scheduling of land complex voxel models at different resolutions, thus significantly reducing the computational complexity while maintaining the expression accuracy of important features.

1. Introduction

With the continuous acceleration of global urbanisation, the efficient use and rational planning of land resources have become the focus of attention for researchers in related field (Wang,2025).As a key component in the Earth's surface system, the land complex covers a variety of elements such as geomorphology, geology, and geomorphology, and its internal structure is complex and functionally diverse (Wang ,2016).The current research for 2D is relatively mature, (Zheng,2023) improved the land use classification accuracy of high-resolution remote sensing images based on the DADNet-CRFs model; (Chenggao,2022) extracted rural residential land from UAV images based on a semantic segmentation framework.However, the traditional grid-based "surface model" topography is unable to effectively express the internal structure of land complexes, and the single-dimensional analysis method is also difficult to meet the demand for multi-dimensional and refined expression in modern land management.

As an emerging three-dimensional modelling method, voxel model provides a new way of thinking for modelling land complexes with its unique spatial expression capability (Niu,2024).With technological advances, voxel models have been gradually introduced into GIS for the representation and analysis of 3D geographic data.In the fields of urban planning and environmental monitoring, researchers have begun to use voxel models to express complex geospatial structures for more accurate ecosystem management (Xie,2018).

Most 3D terrain is modelled using polygon based surface models such as triangular mesh models.For some simple terrain environments, the use of face models to model can often achieve a better visualisation effect, and the 3D visualisation technology based on face models is relatively mature, with many optimisation tools and solutions (Jiang,2016).(Lu,2022)proposes a method for modelling voxel terrain based on process-oriented voxel terrain of DEM data to address the limitations of traditional terrain; (Lai,2017) designs a set of spatially oriented visibility cropping methods to improve the efficiency of voxel scene display; (Wang,2018) proposes an improvement of the node evaluation function based on terrain.However, it requires large computational resources when the model is expressed dynamically.(Yang,2019) proposed a node evaluation function based on viewpoint motion.However, the surface model has defects in representing complex terrain such as caves, arch bridges and hanging walls, such as low efficiency, poor performance, and difficulty in expressing and real-time editing of terrain body data, especially in the simulation of geospatial changes.

Aiming at the above problems, this paper proposes a voxel-based land complex modelling and adaptive resolution expression method, which reduces computational resources, improves the accuracy of the model expression as well as the efficient expression effect by analysing the elemental attributes of the land complex for adaptive analysis, simplifies the model by hierarchical modelling, and achieves adaptive resolution expression with the point of view and the complexity of the terrain as the main influencing factors.

2. Methods

2.1 RulesVoxel modelling of land complexes taking into account the characteristics of physical elements

To achieve body modelling of a land complex, it is first necessary to abstract the most basic units, and then through the combination of these basic units to achieve the description of the various elements of the land complex objects.The basic body element of a land complex is an abstract concept, and its geometric representation is usually a square body element.This square body element has regular geometry and uniform spatial distribution, which can effectively express the internal structure and spatial relationship of the land complex.In order to more accurately describe the complex characteristics of land complexes, this paper further divides the basic body elements into "solid body elements", "liquid body elements" and "gas body elements" according to the state of matter."SolidSolid elements are used to express solid elements such as terrain and buildings; liquid elements are used to express liquid elements such as rivers and lakes; and gas elements are used to express gaseous elements such as atmosphere and clouds.This categorisation enables a better reflection of the physical characteristics and spatial distribution of the different elements in a land complex.This is shown in Figure 1.

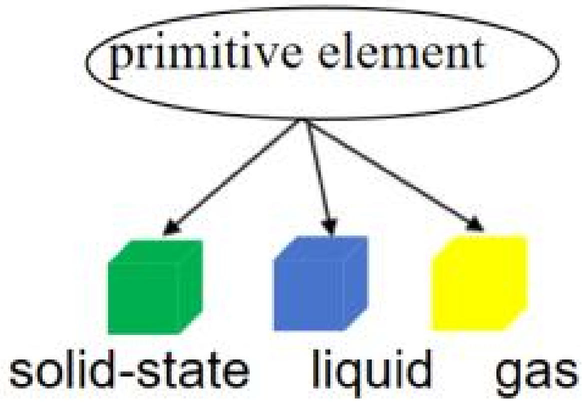

Figure 1. Primitive element.

Since voxel models and voxel mapping methods are not entirely suitable for the modelling and representation of all elements of land complexes.Whether or not to adopt the voxel model approach to modelling in land complex modelling is determined by different uses, different resolutions and the characteristics of the land complex elements themselves.The aim of this study is to analyse the elements that are suitable for voxel modelling and the voxel mapping methods adopted for different elements.As shown in Table 1.

Table 1 Characterisation of the elements of the land complex

Elements		Solid physical element	Fluids physical element	Gas physical element	Order shape	Amorphous	Body modelling	Direct drawing	Indirect body drawing	Element self attribute	Attributes that can be used for body modelling
Geomorphology		●			●		○		◆	Geomorphological type,slope, slope direction	Spatial location
Geological	Plant cover	●			●		—	—	—	Type, height, density, depth, area, area profile	—
	Streams		●			●	○		◆	Flow rate, flow direction, width, depth, area, regional profile	Properties of water: density, temperature, etc.
	Lochs		●		●		○		◆	Width, depth, area, area contour	Properties of water: density, temperature, etc.
	Marshes	●			●		○		◆	Type, area covered	Density
Underground	Subsurface water		●			●	○		◆	Flow rate, flow direction, width, depth, area, regional profile	Density, temperature
	Geological	●			●		○		◆	Soil types, geological formations	Soil type, density, geological formation
	Atmosphere			●						Barometric pressure, air temperature	Barometric pressure, air temperature

● denotes solid, liquid, gas, and definite and indefinite states;
○ denotes that the element can be modelled either as a body or as a surface;
◆ indicates the body drawing method used; - indicates that the body modelling method is not suitable.

The voxel-based land complex modelling method proposed in this paper mainly includes the following steps:

(1) Data fusion and processing: Create a bounding box and determine the mesh size through data fusion and feature extraction.

(2) Determine the object of voxel modelling: Determine the object to be modelled, and obtain the "bounding box" of a given area.According to the application requirements, determine the resolution of the voxel and the elements to be modelled, and extract the elemental properties of the object.

(3) Voxelisation: use the voxelisation method based on the octree structure to voxelise the land complex, in order to reduce the memory consumption and increase the computation speed; the voxel space to be modelled is dissected by using the basic voxels (solids, liquids, and gases); according to the values of the different elemental attributes, interpolation algorithms are used for the 8 corner points of the voxel, and each cubic body is used for the interior of the geographic elements.entity.

(4) Element attribute recording and classification: Determine the specific attributes of the elements and expand the basic voxels into elemental voxels, populate the elements, and record the voxel attributes for subsequent analyses and applications.

(5) Voxel model construction: according to the different attribute values of the 8 corner points, according to the different types of elements, to achieve different element dynamic expressions, to use element attributes to achieve body segmentation, and to analyse the data structure to construct the land complex voxel model.

(6) Data compression and optimisation: judge whether the data need to be compressed, if so, implement data compression; if not, directly construct the land complex voxel model, maintain the integrity of the model, and ensure that all the data are accurate and complete before entering the next stage.This is shown in Figure 2.

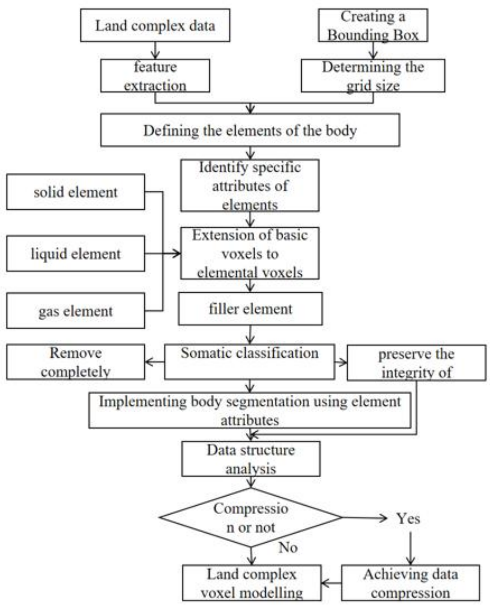

Figure 2.Flowchart of voxel modelling for the method in this paper

2.2 Sight distance

When using the octree LOD model to represent the land complex voxel model, the closer the viewpoint is to the node, the higher the required model resolution level, and the further the distance from the node, the lower the required model resolution level.The relationship between viewpoints and nodes is shown in Figure 3.

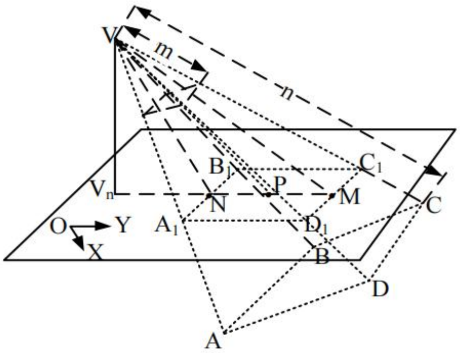

Figure 3 Perspective projection

The viewpoint of the above figure is $x(x_p, y_p, z_p)$ the voxel node is $P(x_0, y_0, z_0)$ and the distance from the viewpoint to the node is:

$$l = \sqrt{(x_p - x_0)^2 + (y_p - y_0)^2 + (z_p - z_0)^2} \quad (1)$$

The square and square operation in Eq. (1) has a certain impact on the system speed and causes excessive consumption of resources, so it is generally simplified and the following formula is used to calculate the distance：

$$l = |x_p - x_0| + |y_p - y_0| + |z_p - z_0| \quad (2)$$

where x_p, y_p, z_p = viewpoint projection coordinates
x_0, y_0, z_0 = voxel node projection coordinates

2.3 Quantitative analysis of terrain complexity

Terrain complexity is a parameter describing the degree of undulation and folding of the terrain surface as a whole or locally, and it is an important indicator of the complexity of the terrain surface.It not only reflects the macroscopic morphological characteristics of the terrain, but also can reveal the microscopic rule of change of the surface, which is of great significance for the modelling and analysis of the land complex.Different terrain factors can describe the terrain characteristics from different perspectives and can express the terrain in more detail.For example, slope reflects the degree of inclination of the land surface; curvature describes the degree of curvature of the land surface, which can reveal the concave and convex changes of the terrain; surface roughness characterises the degree of irregularity of the land surface, which is commonly used in analysing the erosion and deposition process of the land surface; and the degree of terrain undulation reflects the range of changes in the elevation of the land surface, which is an important indicator of the overall degree of undulation of the terrain.According to the characteristics of the land complex voxel model, this paper comprehensively considers four key terrain factors: slope, curvature, surface roughness and topographic relief.These factors can not only comprehensively describe the complex characteristics of the terrain, but also provide an important quantitative basis for the adaptive resolution expression of the voxel model.By combining these terrain factors, this paper constructs a comprehensive terrain complexity model, which provides a scientific basis and technical support for the refined modelling and dynamic expression of land complexes.

2.3.1 Calculation of terrain factors and correlation analysis

1. Slope
Slope gradient describes the degree of local inclination of the surface morphology and is the most important factor influencing the degree of erosion of surface sediments on slopes.In this paper, the third-order inverse distance squared difference algorithm is used to calculate the slope, and the calculation formula is as follows.

$$S = \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2} \quad (3)$$

where $\frac{dz}{dx}$ = rate of change in the horizontal direction
$\frac{dz}{dy}$ = rate of change in the vertical direction

2. Curvature
Planar curvature is the characteristic curvature of terrain in the horizontal direction.

$$P1 = \frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} \quad (4)$$

where $\frac{\partial^2 z}{\partial x^2}$=second-order derivatives of the topographic surface in the x-direction
$\frac{\partial^2 z}{\partial y^2}$ =second-order derivative of the topographic surface in the y-direction
$P1$ = flat curvature

Profile curvature is the characteristic curvature of the terrain in a direction perpendicular to the horizontal.

$$P2 = \frac{\partial^2 z}{\partial x^2}\cos^2(\alpha) + 2\frac{\partial^2 z}{\partial x \partial y}\cos(\alpha)\sin(\alpha) + \frac{\partial^2 z}{\partial y^2}\sin^2(\alpha) \quad (5)$$

where $\frac{\partial^2 z}{\partial x \partial y}$ =mixed second-order derivatives of the topography in the x and y directions
α =Angle in the direction of the slope
$P2$ =sectional curvature

3. Surface roughness
Topographic roughness is generally defined as the ratio of the curved surface area of a surface unit to its projected area on the horizontal plane, and is calculated as follows.

$$R = \frac{S_{\text{meshes}}}{S_{\text{level}}} = \frac{1}{\cos(S)} \quad (6)$$

where S_{meshes}=surface area of surface units
S_{level}=projected area of the surface unit on the horizontal plane
S=slope
R=surface roughness

4.Topographic relief
Topographic relief is the degree to which the difference in elevation within a voxel block reflects the degree of relief of the terrain.

$$D = \frac{1}{d}\max_{i=1,2,\cdots,6}|dh_i| \quad (7)$$

where d=side lengths of terrain blocks

dh_i=Difference between the mean value of the elevation at the midpoint of the edge of the topographic block and the mean value of the elevation at the endpoints of the boundary

D=topographic relief

2.3.2 Comprehensive terrain complexity calculations

In this paper, four indicators of slope, curvature, terrain roughness and terrain undulation are selected as indicators for constructing quantitative analysis of terrain complexity.Combined with equations (3) (4) (5) (6) (7), the mathematical expression of the terrain complexity model in this paper, see equation (8).

$$C = a \times S + b \times \mathrm{P1} + c \times \mathrm{P2} + d \times R + e \times \mathrm{D} \tag{8}$$

where a, b, c, d, e=topographic complexity factor coefficients

2.4 Guidelines for the node evaluation function

According to the idea of LOD algorithm, the smaller the distance of the viewpoint from the voxel node, the higher the resolution of the node, which needs further refinement; the further the distance of the viewpoint from the node, the lower the resolution of the node.Based on this idea, a node evaluation criterion related to distance is established:

$$\frac{l}{d} < \mathrm{Q} \tag{9}$$

where d=size of voxel blocks

Q=distance modifier

The greater the complexity of the integrated terrain, the rougher the surface terrain, the nodes need to be further subdivided, based on which an associated node evaluation law is established:

$$\frac{1}{\mathrm{C}} < \mathrm{q} \tag{10}$$

where C=combined terrain complexity

q=moderators of terrain complexity

Combining the above two parametric factors, the following evaluation function can be established, where the model needs to continue segmentation when f<1, otherwise the segmentation stops.

$$\mathrm{f} = \frac{1}{\mathrm{d} \times \mathrm{C} \times \mathrm{Q} \times \mathrm{q}} < 1 \tag{11}$$

d=size of voxel blocks

C=combined terrain complexity

Q=distance modifier

q=moderators of terrain complexity

l=viewpoint Projection Coordinates Voxel Node Projection Coordinates

f=Evaluation function indicators

The specific technical process of this method is as follows, starting from the point of view, determining the range of screen coordinates and calculating the light vectors, and then determining the visible area and cropping the view area, followed by calculating the view distance and applying the view distance criterion.At the same time, terrain factor analysis is carried out to calculate the terrain factor of the region, analyse the correlation of the terrain factor and carry out normalisation, select the terrain factor indicators with higher principal components through principal component analysis, calculate the integrated terrain complexity and formulate the terrain complexity criterion.Based on the sight distance criterion and terrain complexity criterion, the node evaluation function criterion is constructed.Then, judge whether the node needs to be subdivided, if so, judge whether it is a leaf node of the octree, if so, carry out the node subdivision, otherwise continue to judge whether the node needs to be subdivided.Finally, according to the node evaluation function criterion, determine whether the nodes are visible or not, so as to achieve the adaptive resolution expression of the land complex voxel model.This is shown in Figure 4.

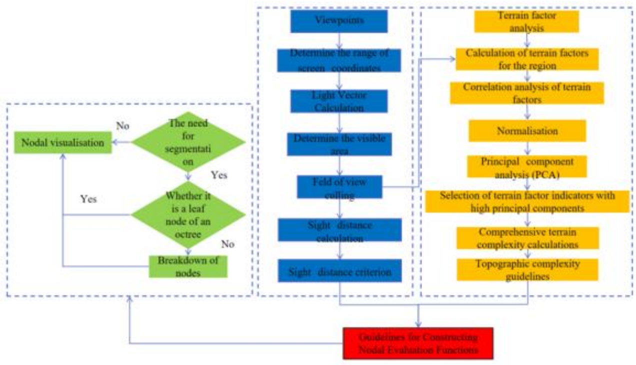

Figure 4 Flowchart of the methodology of this paper

3. Results and analyses

In order to verify the feasibility and validity of the methodology of this paper, the methodology was validated using Python 3.11 programming language to achieve an adaptive resolution representation of the land complex voxel model.The machine tested was a 13th Gen Intel(R) Core(TM) i9-13900HX 2.20 GHz with 16 GB RAM and Windows 11 operating system.The machine graphics card was an RTX 4060.

The experimental data in this paper is from Rongcheng Geothermal Field, Xiong'an New District, Baoding City, Hebei Province, China, and the data type is text-type data in obj format, which is easier to perform editing operations than other binary data.

In this paper, the data are loaded first to ensure the completeness and accuracy of the data, to provide basic data support for subsequent voxel modelling, and to ensure that the data are not lost or damaged during the pre-processing stage before modelling.This is shown in Figure 5.

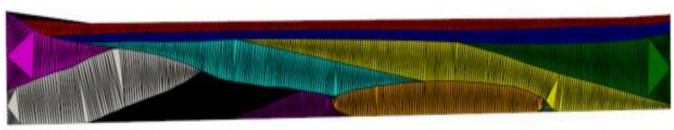

Figure 5 Raw data visualisation

On the basis of the original data model, the boundary information of different elements in the land complex is extracted.By analysing the characteristics of these elements, it is determined which elements are suitable for voxel modelling.Based on the attributes of the elements, the land complex is classified into three basic voxels, namely solid, liquid and gas, and is modelled hierarchically.The purpose of this step is to ensure that the voxel model for each element accurately reflects its internal structure and spatial distribution.This is shown in Figure 6.

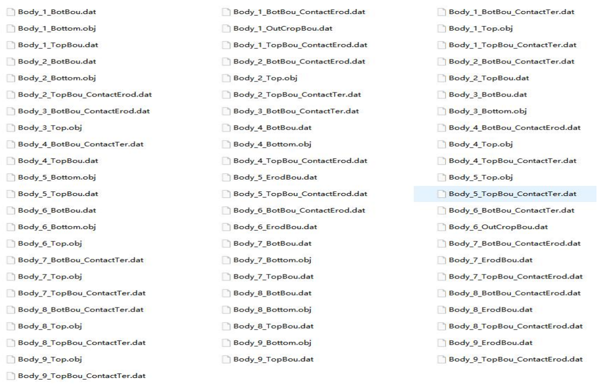

Figure 6 Extracting Boundary Information

After completing the hierarchical modelling, the voxel models of different elements were fused.Through data fusion and feature extraction, the bounding box of the land complex was created and the grid size was determined.Next, the land complex was voxelised using a voxelisation method based on an octree structure to reduce the memory footprint and increase the computational speed.The aim is to integrate the voxel models of different elements into a complete land complex voxel model to ensure the integrity and consistency of the model.This is shown in Figure 7.

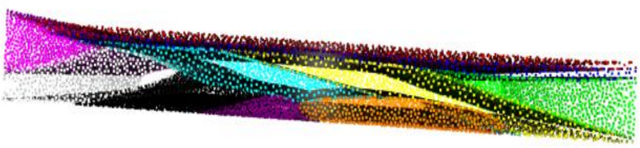

Figure 7 Layered modelling model fusion schematic

After the construction of the voxel model was completed, we realised the adaptive resolution expression of the land complex voxel model according to the node evaluation function criterion designed in this paper.The resolution of the voxel model is dynamically adjusted by comprehensively considering the sight distance and terrain complexity.Specifically, when the viewpoints are close to the voxel nodes, the resolution of the model is higher to show more details; when the viewpoints are far away from the voxel nodes, the resolution of the model is lower to reduce the consumption of computational resources.In this paper, the voxel resolution of 6 m, 4 m and 2 m is used as an example for experimental validation.This is shown in Figure 8、9、10.

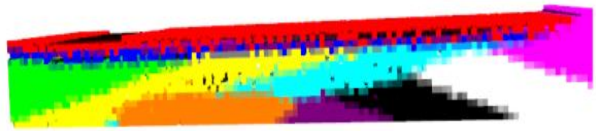

Figure 8 Voxel resolution of 6 metres

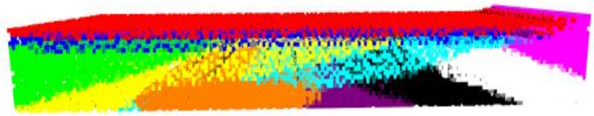

Figure 9 Voxel resolution of 4 metres

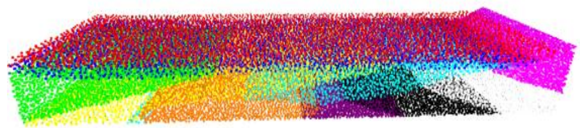

Figure 10 Voxel resolution of 2 metres

In order to verify the superiority of this paper's method, we have analysed the experimental results in terms of voxel data volume and rendering time, and compared this paper's method with the traditional voxel modelling method and the traditional node evaluation function.The experiments were tested with three different voxel resolutions (6 m, 4 m and 2 m) and the results are shown in the following table 2:

Table 2. Comparison of the methods in this paper with traditional methods

Voxel resolution	Voxel modelling methods	Blank voxels /number	Rendering time/s
6 metres	Direct voxel modelling	15526	6.5
	Traditional node evaluation guidelines	15232	6.3
	Methodology of this paper	7025	3.2

4 metres	Direct voxel modelling	15901	10.9
	Traditional Node Evaluation Guidelines	16012	11.1
	Methodology of this paper	7952	5.4
2 metres	Direct voxel modelling	16251	16.3
	Traditional Node Evaluation Guidelines	16034	16.1
	Methodology of this paper	8032	7.3

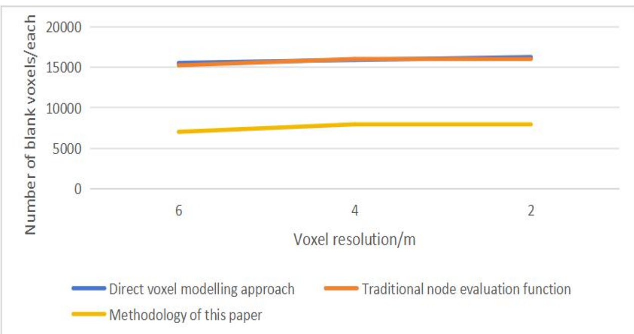

Figure 11 Comparison of the number of blank voxels

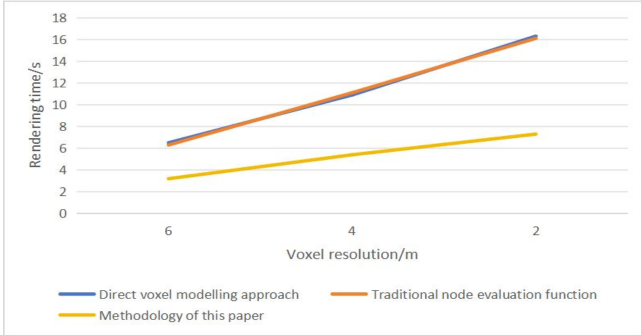

Figure 12 Rendering Time Comparison

From the above table, it can be seen that compared with the traditional voxel modelling method and the traditional node evaluation function, the method of this paper exhibits significant advantages in terms of voxel data volume and loading time.Specifically, in the three cases of voxel resolution of 6 m, 4 m and 2 m, the amount of blank voxel data of this paper's method is reduced by about 55%, 50% and 50%, and the rendering time is shortened by about 50%, 50% and 55%, respectively.The analysis concludes that this paper's method has less blank voxel data volume and faster rendering efficiency than the traditional method in voxel modelling and dynamic representation, both of which are more than 50% better than the traditional method.This significant performance improvement is mainly due to the adaptive resolution expression method proposed in this paper, which dynamically adjusts the resolution of the voxel model by comprehensively considering the view distance and terrain complexity, thus effectively reducing the data redundancy and the consumption of computational resources.

4. Concluding remarks

This paper proposes a voxel-based land complex modelling and adaptive resolution expression method, and experiments show that compared with the traditional method, this paper's method reduces the amount of voxel data by 50% and improves the rendering efficiency by 50%, which significantly reduces the consumption of computational resources, and provides a new technological means for the efficient use of land resources and fine management, which is of great significance for improving the rendering efficiency of urban land 3D scenes.This is of great significance for improving the rendering efficiency of urban land 3D scenes.By comprehensively considering the view distance and terrain complexity, the method in this paper can dynamically adjust the resolution of the voxel model to ensure that the data redundancy and computational burden are significantly reduced while maintaining the expression accuracy of important features.The experimental results show that the method in this paper is better than the traditional method in terms of voxel data volume and rendering time, especially in high-resolution scenes, which can effectively improve the expression effect and rendering efficiency of the model.
Therefore, the next step will be to continue to study how to further apply this paper's method in large-scale urban land scenes, as well as to study the simplification and expression of voxel model data, to further reduce the amount of model data and improve the expression effect of the model, as well as to optimise the real-time interactive performance, in order to enhance its practical application value in land management and urban planning.Future research directions include: 1) exploring more efficient voxel data compression algorithms to further reduce the overhead of data storage and transmission; 2)

investigating the dynamic scheduling mechanism of multi-scale voxel models to cope with the real-time rendering demand of large-scale scenes; 3) combining machine learning and artificial intelligence technologies to improve the automated modelling and optimization capabilities of voxel models; 4) applying the methodology of this paper to more practical scenarios.such as urban underground space management, geological disaster monitoring, etc., to verify its applicability and effectiveness in different fields.Through these researches, the method of this paper is expected to play a greater role in the fields of land resource management, urban planning, environmental monitoring, etc., and provide strong technical support for smart cities and sustainable development.

References

Chenggao, S., Jian, L., Lan, W., 2022. Extraction of Rural Residential Land from Very-High Resolution UAV Images Using a Novel Semantic Segmentation Framework[J].Sustainability,14(19):12178-12178.

Jiang,B.C.,Wan,G.,Fan,C.,X.,2016.Research on modelling battle field environments with voxel models[J].Surveying and mappin g science.DOI:10.16251/j.cnki.1009-2307.2016.09.003.

Lai,G.L.,2017.Voxel Modeling and Expression Methods of Poin t Cloud Data[D].PLA Information Engineering University.

Lu,S.C.,2022.Research on Key Technologies of Voxel-Based Ba ttlefield Environment Construction [D].East China Normal Univ ersity,.DOI:10.27149/d.cnki.ghdsu.

Niu,L.,Wang,Z.,Lin,Z.,2024.Voxel-Based Navigation: A Systematic Review of Techniques, Applications, and Challenges[J].ISPRS International Journal of Geo-Information,13(12):461-461.

Wang,M.Y.,Yu,Q.,Guan,Y.Q.,2025.Analysis of the Application o f Surveying and Mapping Technology in Urban Planning and La nd Use[J].Theoretical studies on urban construction.DOI:10.195 69/j.cnki.cn119313/tu.202503052.

Wang,X.D.,Gong,J.,Liu,W.D.,2017.Construction of land science discipline system based on the concept of land complex [J].Journal of Zhejiang University,47(01):106-117.

Wang,Z.W.,Lv,X.H., Han, X.H., 2018. A Review of Terrain LOD Technology Based on Quadtree Partitioning [J]. Computer Science, 45(04), 34-45.

Xie,Y.X.,2018.Three-dimensional modelling of buildings for inclined photography based on voxel methods[D].Wuhan University

Zheng,K.,2023.Research on High-Resolution Remote Sensing Image Land Use Classification Method Based on Small Sample Image Enhancement and Semantic Segmentation[D].*HenanUniversity*.DOI:10.27114/d.cnki.ghnau.

Yang, Y.P.,2019. Research on Multi-Resolution Terrain Modeling Method Based on Viewpoint Motion and Prediction [D]. Zhengzhou University