

Research Article

Method and Application of Urban 3D Rapid Modeling of Geology Based on CAD Borehole Logs

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Urban 3D geological modeling is one of the key technologies of geological data visualization and spatial analysis. Aiming at the problems of cumbersome modeling process, low modeling efficiency, and accuracy of traditional modeling methods based on borehole data, in this paper, a fast 3D geological modeling method based on CAD borehole data is proposed. The method first designed a method for rapidly extracting borehole log information which is based on .Net API (c#). On this basis, knowledge-driven 3D geological modeling method based on profile data is employed. With these methods, the borehole data in CAD format can be converted to structured data, which can be directly used for data analysis, and the geological knowledge can be analyzed and integrated into the process of three-dimensional geological modeling. The feasibility of this method is verified using the CAD borehole data in the West District of Kaifeng City as an example. The results show that this method can not only realize the rapid construction of urban 3D geological model but also improve the accuracy of 3D geological model.

1. Introduction

The 3D urban geological model can visually display the structure of underground soil mass, which is of great significance for analyzing the geological environment and utilization of underground space to ensuring geological safety during the exploration of underground space [1–3]. Borehole histogram is one of the principal maps of 3D geological modeling. Generally, manual input is usually used to extract borehole information in CAD format and used for 3D geological modeling. Due to the diversity of borehole sources and stratigraphy division standards, the generated geological model is often inconsistent with geological knowledge, which requires much manual intervention. Therefore, the traditional 3D modeling method of urban geology based on borehole data in CAD format has low accuracy and efficiency [4].

At present, borehole data is the main data source of urban 3D geological modeling [5–7]. There are many methods to constructing 3D models from borehole data, such as section connection method, multilayer digital elevation model (DEM) modeling method, the stochastic modeling method, and GTP-based modeling method. The profile connection method [8] usually requires the establishment of borehole database, the preprocessing and stratum division of borehole data, and then the automatic interpolation connection of the layers of the same stratum to generate the ground layer. The boreholes without stratum information are inserted into the corresponding virtual control points, and the stratum pinch-out line in line with the geological facts is formed according to the geological profile. Finally, the geological body frame model is generated from the ground level. This modeling method

adds geologists' understanding of geological objects and reduces the uncertainty of formation information between boreholes. Therefore, the established 3D geological model has high accuracy, but the modeling efficiency is low, and it easily leads to topological errors [9, 10]. Multilayer DEM modeling [11] constructs multilayer DEM according to the stratum on the borehole. The irregular triangulation of each layer adopts Delaunay triangular mesh method. Based on the multilayer DEM modeling method, after intersecting with the ground layer, the solid stratum model is established by using the stratum splicing method. Compared with volume model, multilayer DEM has the advantages of simple topology, fast modeling speed, and easy cutting and analysis. However, there are still defects when the application stratum is extinct. The stochastic modeling [12] method can better describe the random distribution and uncertainty characteristics of geological blocks and geological region boundaries in space. However, the attribute structure of these geological bodies is difficult to describe and model because the available data is usually very scarce and the data requirements of this method are very strict (for example, dense boreholes or sections are required). The GTP-based modeling [13] is generated based on drilling data. Each stratum interface forms a geological body through vertical connection. The GTP method cannot interpolate the surface and stratum, and the elements are too sparse, which lead to a model that is not smooth and not easy to interpolate.

The urban Quaternary shallow sediment strata are complex, with common stratigraphic pinching and missing, many lenses, and a certain rhythm. Its complex structure is a challenge to the existing 3D geological modeling methods. In recent years, some scholars have attempted to use cross-section methods [14] and explicit and implicitly integrated 3D geological modeling methods [15], for geometric fusion of complex geological structure models of urban shallow sediments, and achieved good results, which provided ideas for this paper.

In order to raise the utilization efficiency of CAD format borehole data and make the results of 3D geological modeling more reasonable, a method that can quickly and intelligently identify and process CAD format borehole data was proposed. Meanwhile, section information is integrated into the modeling process to reduce the pinch out and the lens caused by data errors and improve the rationality of the three-dimensional geological model.

In Section 2, this paper describes the related research work of borehole data extraction and the process of automatically extracting information from a CAD borehole log. The construction flow of 3D urban geological model is introduced in Section 3, including borehole data preprocessing, stratum standardization, and the integration of geological knowledge to optimize the 3D geological modeling process based on the existing profile, to obtain a reasonably usable 3D geological model. In Section 4, this paper displays the experimental results in the 3D modeling of urban geology in Kaifeng by using the method proposed in this paper. In Section 5, conclusions and suggestions are put forward for future improvement.

2. Extraction of Borehole Data Based on .Net API (c#) CAD Format

The materials and methods section should contain sufficient detail so that all procedures can be repeated. It may be divided into headed subsections if several methods are described.

2.1. Research Status of Borehole Histogram Information Extraction. Generally, manually extracting borehole data has disadvantages of high error rate and low efficiency. In order to make the process of extracting borehole histogram information intelligently, some scholars have carried out relevant research. For instance, Zhang developed the borehole histogram information acquisition software based on MAPGIS K9 and realized the automatic generation of Excel file for the layered information of borehole histogram in MAPGIS K9 and MAPGIS 6x format [16]; Zhang et al. proposed an algorithm to quickly obtain information from borehole histogram based on machine learning to process and convert the extracted information into geospatial data [17]. However, there is nearly no research on the commonly used CAD format of borehole histogram. At present, the research on the extraction of CAD drawing text information has been relatively mature, and commonly used methods include feature point recognition, table conversion, coordinate positioning, and modular attribute text [18–22], but they are highly industrial. The borehole histogram contains many nonvertical table segmentation points and pattern filling, and they cannot be precisely used as the borehole histogram. Therefore, based on .Net API (c#), a method of rapidly and automatically extracting information of borehole histogram was proposed to export the data to Excel.

2.2. Extraction of Borehole Histogram Information Based on .Net API (c#) CAD Format. With the secondary development technology of Excel and autoCAD.net (c# language), the plug-in for batch extraction of borehole histogram information is compiled. The overall process is shown in Figure 1.

- (1) Obtain the frame of the borehole histogram. Firstly, use the entity object classification entity sort to get the object sets; the polyline frame has a length of 1014 mm and an area of 62370 mm². Then, respectively, define border ID, border point sets, object ID in the border, text sets, line sets, the vertical line sets, horizontal line sets, and pattern fill sets
- (2) Obtain the required objects in the frame. Get the required object sets in the frame through `geteveryarea`, including framesets, object sets, and object detail sets (single-line text and multiline text; straight line; pattern fill)
- (3) Obtain the contents of the required objects in the frame. The obtained content is mainly used for three-dimensional geological modeling, including borehole number, coordinate X, coordinate Y, orifice elevation, bottom depth, layer number, and lithology. Through `getdatafromobject`, the content of the

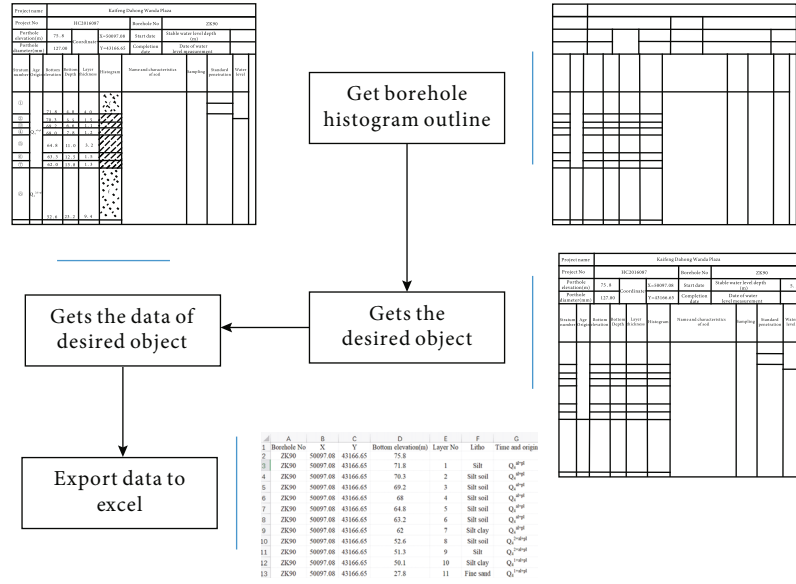


FIGURE 1: The overall process of borehole histogram information extraction.

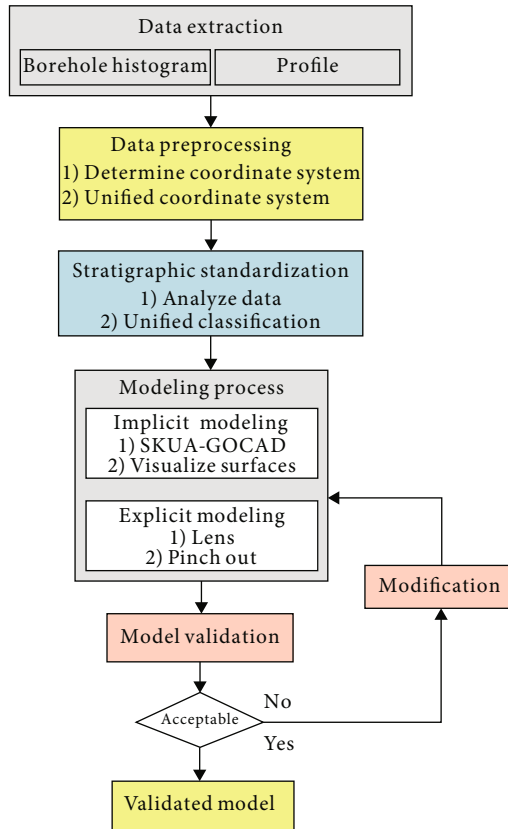


FIGURE 2: The urban 3D geological modeling process based on borehole data.

object, including the borehole number, orifice elevation, coordinate X , and coordinate Y , is obtained according to the position information of text. According to the text content of layer bottom depth, layer number, and lithology, the range is obtained,

TABLE 1: Engineering geological stratification of shallow soil in Kaifeng west area.

Engineering geological layer	Soil ID	Horizon ID
(1) Layer	Fill soil	1
(2) Layer	Silt	2
(3) Layer	Silty soil	3
(4) Layer	Silty clay	4
(5) Layer	Silty soil	5
(6) Layer	Silty clay	6
(7) Layer	Silty soil	7
(8) Layer	Silty clay	8
(9) Layer	Silty soil	9
(10) Layer	Fine sand	10
(11) Layer	Silty clay	11
(12) Layer	Fine sand	12

and then, the specific value is assured according to the fact that the single-line text Y is less than the minimum Y coordinate of the text content. The algorithm of judging whether the point is in the frame adopts the ray method, which means the point is within the polygon when the number of times of the ray passing through the polygon boundary is odd

- (4) Export the data to Excel. The reading and writing operation of the Excel table in the c# program is realized by referring to the Microsoft Excel type library

3. 3D Urban Geological Modeling Process

Extracted borehole information mentioned above can be directly used for modeling the 3D geology of a small area. However, due to massive geological units and complex

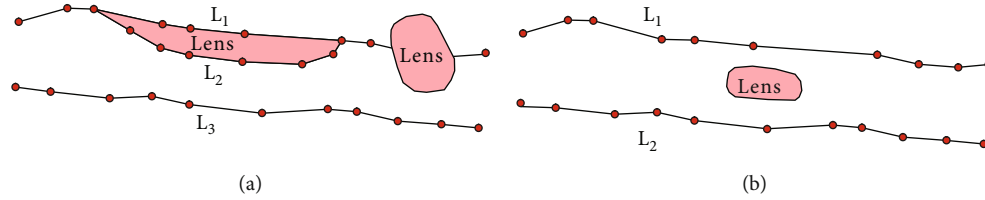


FIGURE 3: Processing of lens body.

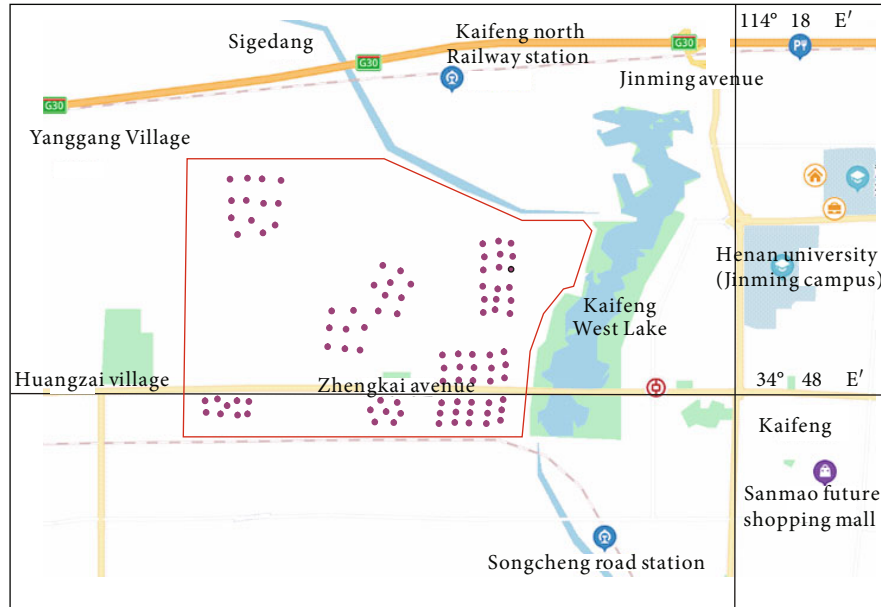


FIGURE 4: Geological research area in Kaifeng City (modified by Google Maps).

geological relations in urban areas, the modeling should follow the process in Figure 2.

3.1. Borehole Data Preprocessing. As the drilling data is collected from different engineering survey units, the coordinate system and elevation system of the drilling histogram are inconsistent. Some engineering surveys only use the assumed coordinate system and elevation system. Therefore, before 3D geological modeling, it is necessary to simplify the coordinate system of borehole data to the independent coordinate system of Kaifeng City. In this paper, ArcGIS software is used for projection transformation among coordinate systems, and the method of remeasurement is used for the assumed coordinate system.

3.2. Stratum Standardization. Because engineering surveys are conducted by different Engineering Survey Institutes and the stratigraphic division standards in each region are not consistent, especially in urban areas, the data are difficult to be unified, resulting in different independent local geological models. Therefore, it is necessary to standardize the strata of the preprocessed borehole data before urban 3D geological modeling. Furthermore, engineering geological layers intersect each other and have intricate relationships; the problem of dividing engineering geological sequences

has become the key issue of three-dimensional geological modeling [23].

In recent years, some scholars made beneficial exploration on stratigraphic standardization [24]. For instance, Zhao et al. introduced the Support Vector Machine (SVM) to classify the strata. Even for the sample set with a small scale, this method can obtain the optimal global solution that minimizes the risk of the data structure, but the final training result is less accurate [25]. Based on the theory of geological interpretation methods, Li et al. used the principle of the high frequency of occurrence of strata to determine the stratigraphic sequence fully automatically and introduced the idea of subborehole recursion using surface modeling methods [26]. Liu et al. designed strata division methods based on a convolutional neural network, but the neural network retains incorrect training weight during the classification process, which leads to inaccurate results when the sample size is small [27]. Zhang et al. (2020) proposed a process of prestoring geological knowledge in a geological data corpus and then classifying the process, but the specific recognition rate of geological symbols is minimal. The above method solves the problem of standardizing stratum to a certain extent but still has defects of requiring merging and generalization, such as complex lithology and stratigraphic cross repetition.

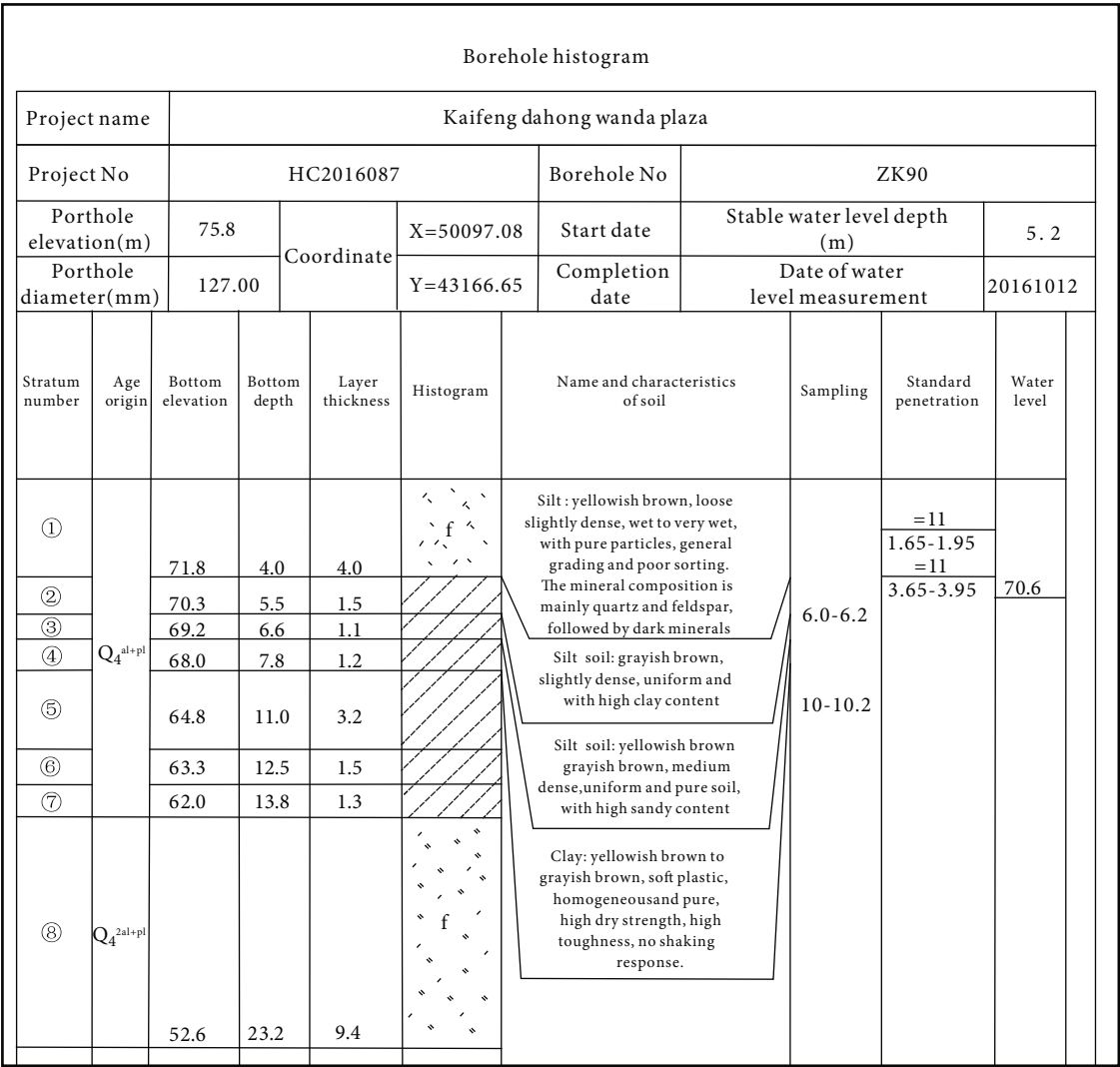


FIGURE 5: An original borehole log in Kaifeng City.

TABLE 2: Extract information from an original borehole log.

	A	B	C	D	E	F	G
	Borehole No.	X	Y	Bottom elevation (m)	Layer No.	Litho	Time and origin
1	ZK90	50097.08	43166.65	75.8			
2	ZK90	50097.08	43166.65	71.8	1	Silt	Q ₄ ^{al+pl}
3	ZK90	50097.08	43166.65	70.3	2	Silt soil	Q ₄ ^{al+pl}
4	ZK90	50097.08	43166.65	69.2	3	Silt soil	Q ₄ ^{al+pl}
5	ZK90	50097.08	43166.65	68	4	Silt soil	Q ₄ ^{al+pl}
6	ZK90	50097.08	43166.65	64.8	5	Silt soil	Q ₄ ^{al+pl}
7	ZK90	50097.08	43166.65	63.2	6	Silt soil	Q ₄ ^{al+pl}
8	ZK90	50097.08	43166.65	62	7	Silt clay	Q ₄ ^{al+pl}
9	ZK90	50097.08	43166.65	52.6	8	Silt soil	Q ₄ ^{2+al+pl}
10	ZK90	50097.08	43166.65	51.3	9	Silt	Q ₄ ^{2+al+pl}
11	ZK90	50097.08	43166.65	50.1	10	Silt clay	Q ₄ ^{1+al+pl}
12	ZK90	50097.08	43166.65	27.8	11	Fine sand	Q ₄ ^{1+al+pl}
13	ZK90	50097.08	43166.65				

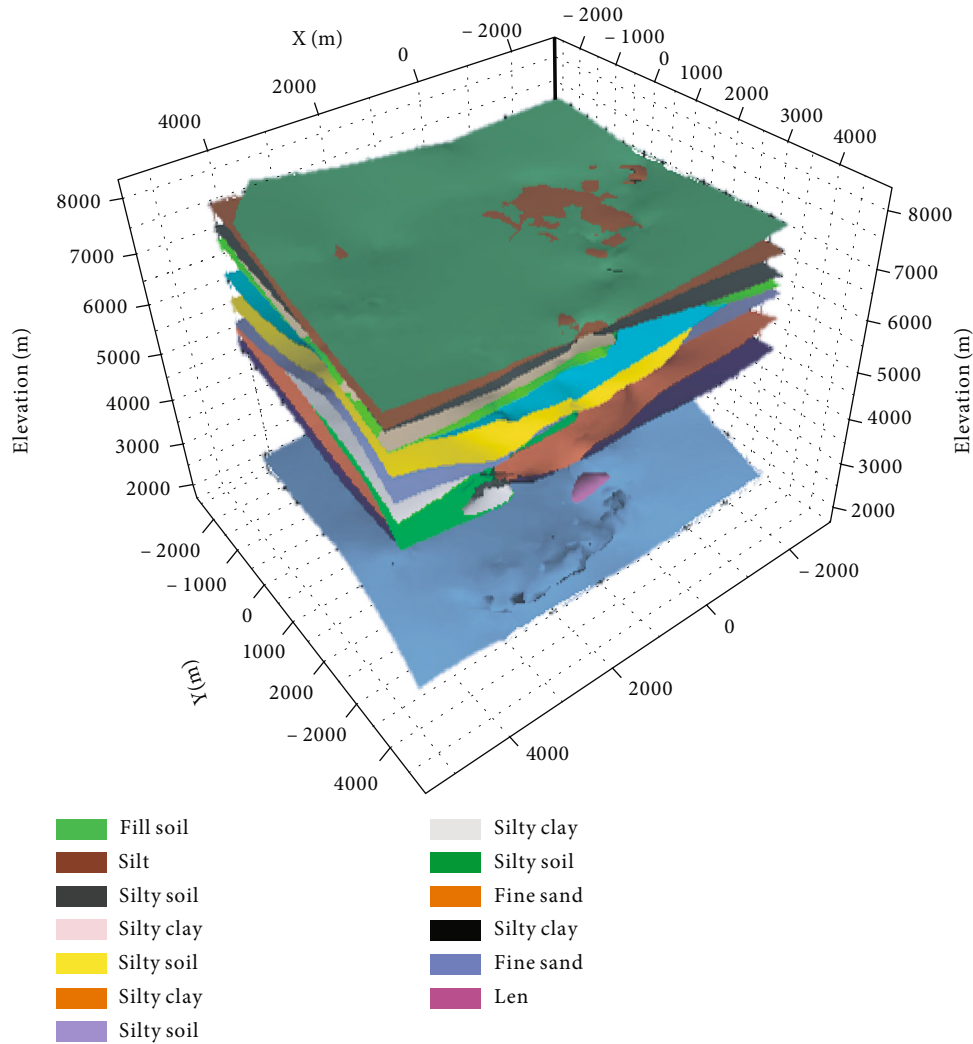


FIGURE 6: Stratum layer model.

According to the collected engineering geological data, there are numerous lithology types of shallow soil in the West District of Kaifeng City, including silt, silty clay, clay, and fine sand. The intricate combination relationship between these different lithologies increases the difficulty of model establishment, making it difficult to display in the three-dimensional geological model. Therefore, it is necessary to merge and generalize the strata reasonably. The stratigraphic division method mentioned above cannot be used directly. After analyzing and sorting engineering geological borehole data, based on the physical and mechanical properties, the stratum standardization further merged the lithology of the shallow soil in the West District of Kaifeng City and divided the shallow soil above 45 m into 12 areas. Engineering geological layers are shown in Table 1.

3.3. Combined with Engineering Geological Profile. The stratum between boreholes is complex, and it is difficult to build a three-dimensional geological model meeting the engineering requirement just based on a single borehole data and a

specified interpolation algorithm [28]. In this paper, the method of using the auxiliary section to integrate the geological knowledge into the three-dimensional geological modeling was proposed, making the model more reasonable and realistic. According to the current research [29], in the modeling process, the geological profile is mainly used in three aspects: (1) determine the relative position of each stratum pinch-out point between the two borehole tracks according to the exploration profile and expert knowledge and experience, and generate a pinch-out line in line with the geological facts; (2) there are two cases for the lens body. One is the lens connected with the upper or lower layers; while connecting stratigraphic section lines, the length of the upper and lower boundary lines of the lens body should be extended to the unified length of the whole stratigraphic line (Figure 3(a)). Similarly, the pinch out of the formation can also be handled in this way [30]. The other is that the lens is in the middle of the upper and lower layers (Figure 3(b)). The upper and lower layers of the lens are determined according to the exploration profile, and the

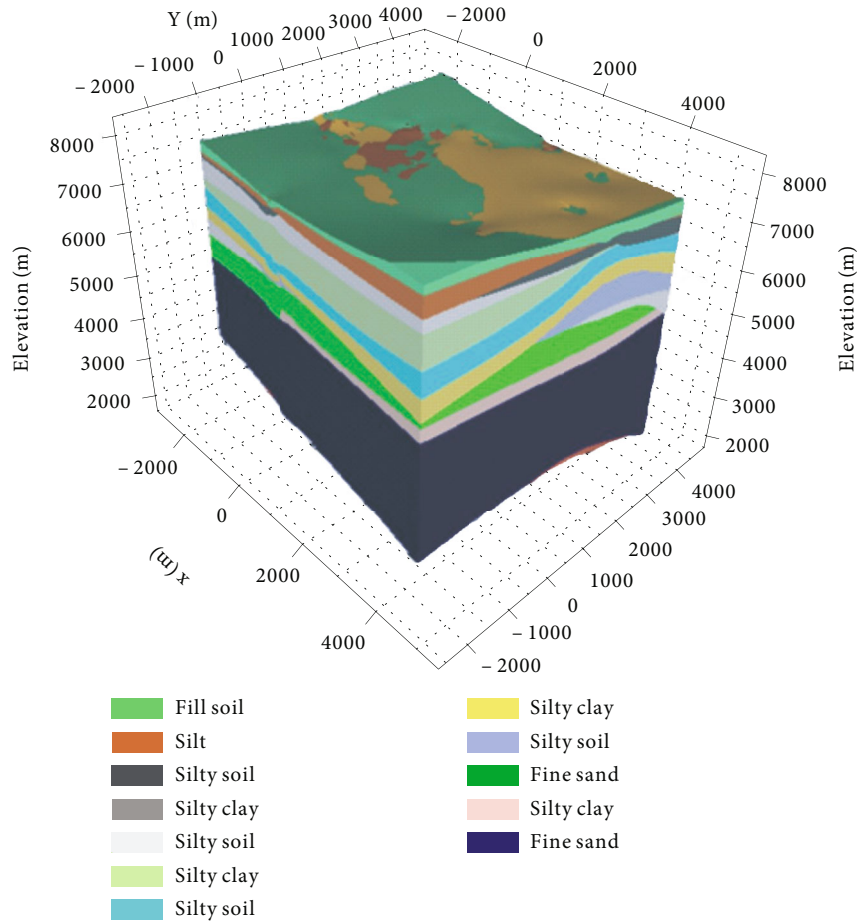


FIGURE 7: 3D geological model.

volume model is constructed by interpolation; (3) after modeling, the result is compared with the stratigraphic line data of the profile to adjust the stratigraphic boundary; then, new points are added to the stratigraphic interpolation calculation to adjust the spatial form of the geological model.

3.4. Extract Layered Data and Generate Stratigraphic Layer Model. Unify the stratigraphic sequence by adding 0-thickness layers [31, 32] to make all boreholes have the same layering sequence. The data set of each layer is obtained through simple sorting in Excel; then, the data set of each layer is spatially interpolated to generate the layer model.

3.5. The Generation of 3D Geological Model. Based on the layer model, a three-dimensional geological model is generated. For local lenses, manual creation is selected to create a separate lens model in this work according to the stratification information of lenses in boreholes (layer top and layer bottom data, etc.). Finally, the lens is merged into the corresponding main layer to form a complete three-dimensional geological structure model.

4. Application

In this paper, taking the Kaifeng west area as input data, we used the data processing flow of urban 3D geological model-

ing based on borehole data (CAD). The ultimate urban 3D geological model was built in the 3D geological visualization software platform SKUA-GOCAD, and good results have been achieved in the practice of the project.

4.1. SKUA-GOCAD. SKUA-GOCAD is a new generation of geological modeling software with workflow as the core developed by Emerson, which realizes semi-intelligent modeling, and is commonly used in engineering geology, mining development, petroleum engineering, and water conservancy engineering [33–35].

4.2. Study Area. As shown in Figure 4, the study area is located in the West District of Kaifeng City and belongs to the high-tech industrial park. The key research area starts from 12th Street in the west, West Bank of Kaifeng West Lake in the east, Fuxing Avenue in the north, and Jin'an road in the south. Since the area was a development zone in 1998, many engineering construction activities were performed. This paper studies the area based on the engineering survey data in the area, and there are many borehole data in CAD format made by different survey institutes. Therefore, the rapid extraction, standardization, and multisource data integration of these data are difficult, which is also the original intention of this paper to propose 3D urban geological rapid modeling.

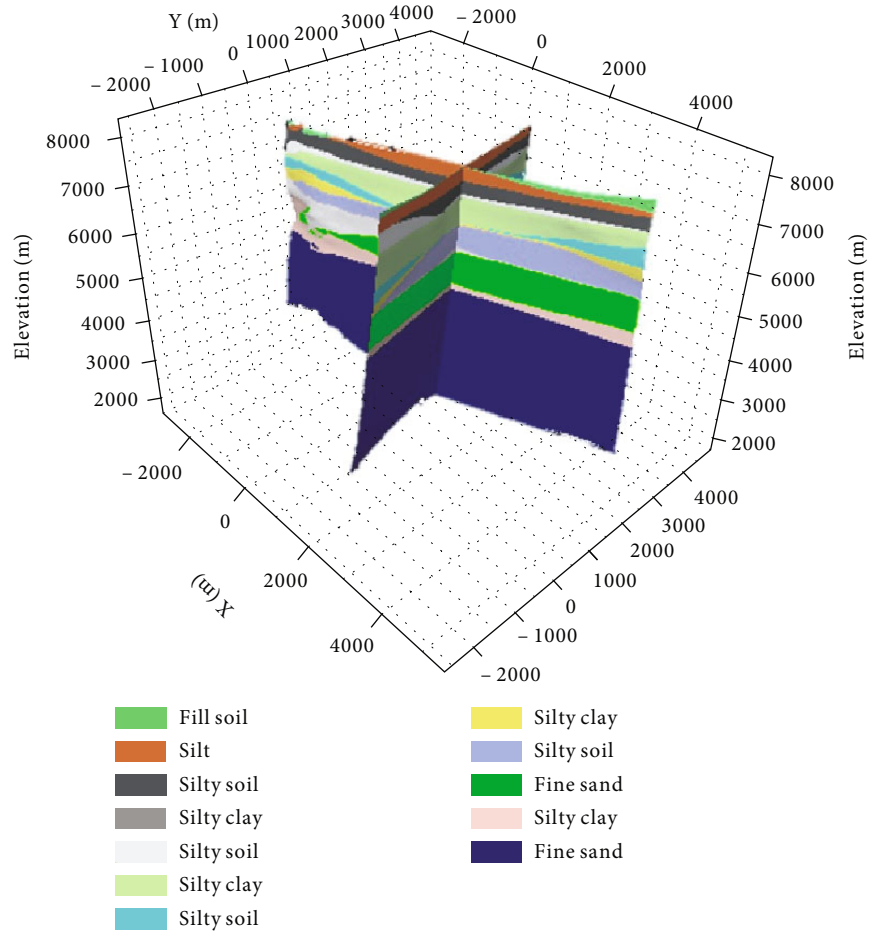


FIGURE 8: Section.

4.3. Specific Implementation Process

4.3.1. Processing Flow of CAD Borehole Diagram. There are many borehole histograms in CAD format in the project, and some contain one borehole data (Figure 5), and others contain multiple borehole data. For the borehole histograms of these different templates, the information can be extracted quickly through the borehole information extraction plug-in based on .Net API (c#). The specific process is as follows: Firstly, open the borehole data in CAD format to extract information, enter netload to load the plug-in from the command line, and then, enter zke command to pop up the saved Excel dialog box. At last, borehole information can be extracted after saving, as shown in Table 2.

4.3.2. Modeling Flow

(1) Stratum layer model

After loading the borehole data from the database, the point set data of separate boreholes in the same stratum can be obtained. The point set data in the same stratum can be spatially interpolated using Kriging interpolation technology to generate the layer of each layer (Figure 6).

(2) 3D geological model

Semi-intelligent modeling is carried out by using SKUA-GOCAD workflow modeling. The specific process is as follows: firstly, the stratigraphic sequence is defined, and the contact relationship between stratigraphic sequences is determined. Then, the scope of the work area is defined to establish the layer model. Finally, the crossrelationship between the layers is checked, and the stratigraphic sequence is used to create the middle layer. The model can be seen in the 3D display area (Figure 7). In order to view the model, the Z value is enlarged by 10 times.

In addition, the model can be simplified in two ways to display the internal information of the model. One is the section method, which can cut the model at any position parallel to the coordinate axis (Figure 8), and the other is the slice method, which can cut along any direction, and the cutting effect is shown in Figure 9.

(3) Pinch out and lens processing

For the pinch out of the stratum and the lens connected with the upper or lower layers, the length of the upper and lower boundary lines in the profile line is extended to the

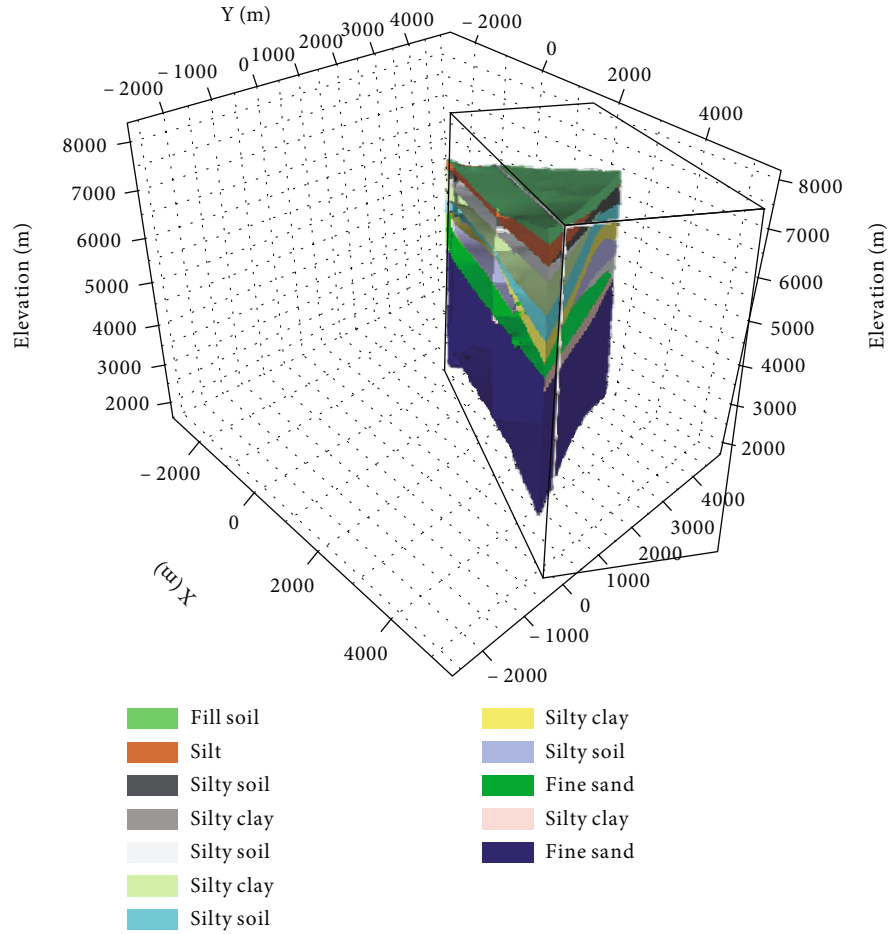


FIGURE 9: Slice.

uniform length of the entire stratigraphic line by adding a zero-thickness layer, then building a geological model together with the layers.

According to the layered information of the lens in the exploration profile or borehole histogram (layer top and layer bottom data, etc.), the human-computer interaction tools allow the software platform to make a separate lens model (Figure 10). Finally, the lens is merged into the corresponding main layer to form a complete three-dimensional geological model.

(4) Model verification

Model verification is to compare the 15 boreholes reserved in the modeling process with the data at the same location in the model. An example of borehole verification is given in Table 3. Model verification shows that the three-dimensional structure model conforms to the geological law and is basically consistent with the actual geological situation, indicating that the model can visually display the stratigraphic distribution and structural characteristics within the depth of 45 m in the west area of Kaifeng. However, the elevation of local strata is still different from the actual situation; the principal reason may be that the bore-

hole distribution is uneven, resulting in stratum differences when discrete smooth interpolation is used.

5. Discussion

Borehole data is the main data source of urban 3D geological modeling. Many methods have been used to construct 3D geological models from borehole data, such as the section connection method [8], multilayer DEM modeling method [11], stochastic modeling method [12], and GTP-based modeling method [13]. However, these methods are not suitable for 3D geological modeling of urban shallow sediments. The existing 3D geological modeling methods of display and implicit integration [15] have high requirements for modelers. The method proposed in this paper has certain universality. Its modeling process includes intelligent extraction of drilling data, preprocessing of drilling data, stratum standardization, combination of profile, explicit and implicit modeling, model verification, and the generation of the model. The above modeling experimental results show that the modeling method proposed in this paper can be well applied to urban geological modeling based on geotechnical engineering borehole data, and this method is effective for

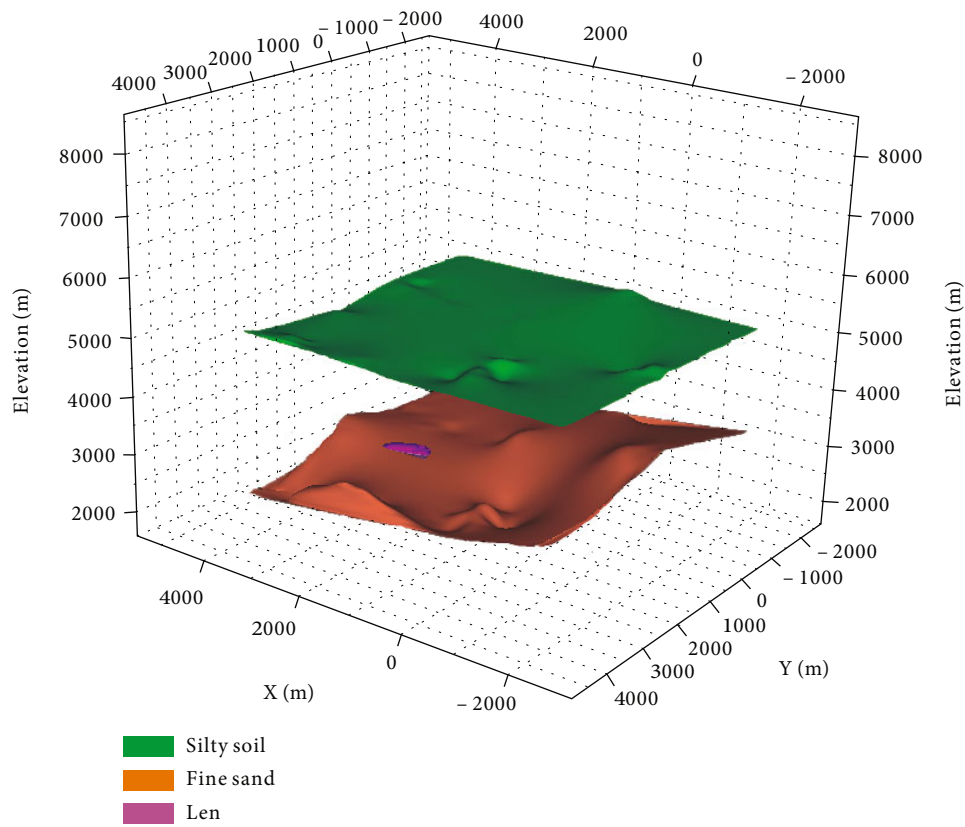


FIGURE 10: Lens between two layers.

TABLE 3: Borehole verification.

Borehole no	Raw data		Model data		Error	Error analysis
	Bottom elevation/m	Lithology	Bottom elevation/m	Lithology		
ZK126	72.85	Silt	72.38	Silt	0.47	Stratigraphic correspondence
ZK126	71.15	Silty soil	71.48	Silty soil	0.33	
ZK126	69.95	Silty clay	70.08	Silty clay	0.13	
ZK126	69.15	Silty soil	68.38	Silty soil	0.77	
ZK126	66.75	Silty clay	66.18	Silty clay	0.57	
ZK126	64.65	Silty soil	/	/	/	Stratigraphic amalgamation
ZK126	62.45	Silty soil	62.98	Silty soil	0.53	
ZK126	60.95	Silty clay	/	/	/	
ZK126	58.65	Silty clay	59.58	Silty clay	0.93	Stratigraphic correspondence
ZK126	57.45	Silty soil	57.68	Silty soil	0.23	
ZK126	53.35	Fine sand	52.98	Fine sand	0.37	
ZK126	51.15	Silty clay	50.68	Silty clay	0.47	
ZK126	27.45	Fine sand	28.03	Fine sand	0.58	

most urban geological models. However, some outstanding problems must be addressed, for instance, intelligent stratum standardization scheme; considering the complex lithology of the study area, the three-dimensional geological model has difficulty showing the crossrepetition of the stratum, it is necessary to reasonably merge and summarize the

stratum, and the intelligent stratum standardization method is difficult to adapt. In this study, professionals were used for reasonable consolidation and manual generalization. In the future, it is necessary to strengthen the intelligent research of stratigraphic standardization. Secondly, the experimental case does not include faults, folds, or other geological

structures; whether the method proposed in this paper is applicable to these more imported urban geological models needs to be further verified.

6. Conclusions

This paper presents an urban 3D geological modeling method based on CAD format borehole data, which can be applied to the rapid 3D geological modeling of the city through intelligent extraction of borehole data, standardization of strata, and the section knowledge.

- (1) This paper mainly introduces intelligent extraction of CAD format borehole data and section data, which overcomes the shortcomings of the high error rate and low efficiency of traditional manual extraction and makes the whole 3D geological model more intelligent and automatic
- (2) This method can not only ensure the modeling accuracy but also meet the requirements of geologists for rapid modeling in terms of modeling efficiency. Therefore, this method can be widely used in urban 3D geological modeling
- (3) However, there are still many details to be noticed. On the one hand, the process of formation standardization involves formation merging and generalization, which still need professional guidance. On the other hand, the selected research area in this paper is the West District of Kaifeng City, which does not contain sufficient complex geological conditions such as faults, folds, and karst. Whether the method proposed in this paper is applicable to these more intricate urban geological models needs to be further verified

Data Availability

The data reported in this article are available from the corresponding author upon request.

Disclosure

Meanwhile, the sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

The manuscript is approved by all authors for publication.

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