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RESEARCH ARTICLE

On the topographic entity-oriented digital elevation model construction method for urban area land surface

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Abstract Human activity transforms a land surface into a complex surface where artificial and natural landforms coexist and continuous and emergent landforms merge. In this background, the problems of conventional digital elevation models (DEMs), such as morphological distortion, complicated updates, and lack of information, are increasingly prominent. This study proposes a new idea of DEM construction based on the concept of geographic ontology. First, landforms with common features are abstracted into a certain type of topographic entity based on their morphologies and semantics. For each type of topographic entity, a DEM was constructed independently based on the available elevation information and other information about the semantics and spatial relationships. Second, individual DEMs were merged into a complete DEM following certain rules. A 1 km^2 area located in the suburb of Nanjing, Jiangsu Province, China, was selected as the experimental area. The effectiveness of the model construction method proposed in this study was verified. The results show that the DEM constructed according to the idea of this study has a significantly better performance than the conventional DEMs. The constructed DEM in this study can well represent ground objects, such as slopes, farmland, and ditches. In particular, the constructed DEM ensures the morphological accuracy of the ground objects.

Keywords topographic entity, DEM, urban area, artificial strip terrain, morphological accuracy

1 Introduction

A digital elevation model (DEM) is a digital cartographic/geographic data set of elevations in *xyz* coordinates, and the terrain elevations of ground positions are sampled at regularly spaced horizontal intervals (Burrough and McDonnell, 1998; Aguilar et al., 2005). DEMs are the basic data set utilized in geo-scientific analysis and process simulations (Hutchinson and Gallant, 2000; Pike, 2000), and they have been widely employed to describe terrain characteristics (Fisher, 1991) in hydrological (Moore et al., 1991; Murphy et al., 2008), environmental protection (Li and Chen, 2005), natural disaster analyses (Kawabata et al., 2010), and other scientific fields as well.

Present research on DEM construction focuses on the following two aspects. 1) A focus on data sources adopting a single data source or multisource data to build DEM. The instances include ground measurement data (Favalli and Pareschi, 2004), aerial photogrammetry data (Baltsavias et al., 2001), airborne laser scanning LiDAR data (Baltsavias, 1999), and airborne interferometric synthetic aperture radar (InSAR) and unmanned aerial vehicle imagery data (Colomina and Molina, 2014; Diaz-Varela et al., 2014). The above researches are contemporarily significant data sources for the construction and production of DEM. 2) A focus on modeling methods. The previous stage of DEM modeling methods primarily concentrated on the construction and optimization of spatial interpolation methods. For instance, in addition to the classical interpolation methods, such as inverse distance weighting (IDW), spline, Kriging and so on, Yue et al. (2007) developed the high-accuracy surface modeling (HASM) method, and related scholars have been improving the model in the past ten years (Yue et al. 2010a, 2010b and 2020; Jiang et al., 2018). Compared to the conventional interpolation method, the accuracy of the DEM construction was prominently elevated. Hutchinson (Hutchinson, 1989; Yang et al., 2007), based on thin-plate splines, vectorized river networks as auxiliary data by combining terrain enhancement algorithms to realize a correct DEM

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algorithm(ANUDEM) for hydrological relationships. On the basis of multiquadric functions, DEM interpolation algorithm was developed by Chen et al. (2013 and 2016), which is applicable to DEM construction when the elevation data have coarse errors. In the last few years, many scholars have achieved a better resolution and precision in different DEMs by joining DEM data sources with construction methods. For digital elevation model (DEM) data from different sources, a variety of DEM data fusion methods, such as the self-consistency technique (Schultz et al., 1999), fast Fourier transform (Karkee et al., 2008; Chen et al., 2010.), sparse representation (Papasaika et al., 2011), Kalman filtering (Slatton et al., 2002), weighted average method (Roth, et al., 2002; Podobnikar, 2005; Reinartz, 2005; Yin et al., 2012), and artificial neural network method (Yue et al., 2017), have been developed.

What needs to be explained is that most related researches on DEM construction has been treated the ground surface as a continuous surface. But the fact is that the terrain is an object with both gradual and abrupt changes. In particular, with the continuous intensification of human activities on the ground surface reconstruction, the formation of many artificial terrain, such as roads, dams, farmland, etc. continues to appear. These artificially reconstructed terrains have a large scale, strong effects, different shapes, and consistency with the surrounding terrains. Traditional modeling approach is inappropriate for the expression of artificial terrains and may even cause large errors, especially obvious morphological errors. Some scholars have begun to do some researches on the DEM construction methods of special terrains made by human activities. For example, Wang et al. (2009) raised the feature-embedded DEM, terraced DEM (Zhao et al., 2015) and grid and triangulated irregular network (TIN) hybrid structure DEM (Yang et al., 2005), which well preserved the local morphological characteristics of the ground surface. However, the limitations of this type of study are obvious. These studies consider the previously mentioned artificial landforms as independent special cases rather than parts of the land surface. These studies do not effectively explore problems in DEM construction when these artificial landforms overlap natural landforms.

The real world is a three-dimensional complex, which cannot be described using a unified model. However, the real world can be categorized into different surface units according to the local morphology, which is especially obvious in areas with significant human activity. Different topographic units have different morphologies and distinct boundaries. In DEM construction, the morphological characteristics, spatial relationships, and semantic relationships of different surface units must be considered to achieve categorized model construction with different surface units. To achieve this goal, this paper propose the concept of topographic entity based on the idea of geographic ontology and describe the spatial relationship and semantics of topographic entities. A typical experimental area is selected and a large-scale topographic map is taken as the basic data source. This paper define different topographic entities, extract their boundaries, and construct DEMs. The differences between the model construction results of this study and those of the conventional methods were also discussed from the perspectives of elevation accuracy and morphological accuracy. Finally, to enhance the generality of the DEM construction method proposed in this study, the paper discuss the feasibility and basic ideas of the topographic ontology-oriented DEM construction based on aerial image data and light detection and ranging (LIDAR) point cloud data, which are easily accessible.

2 Relevant concept

2.1 Geographic ontology

Chen et al. (2006) considered geographic ontology a system that consists of objects (or entities) of common features with certain relationships. The system is abstracted from the knowledge, information, and data related to the field of geographic science. The system is further conceptualized and clearly defined, becoming a theory and method with formal expression. (An et al., 2006). Further elaborated the concept of geographic ontology. A geographic space is composed of different types of geographic entities. An ontological concept consists of a series of geographic entities with the same features and behaviors. Each geographic entity can be projected onto an object in the computer world. Each object has geometric properties, time information, and topological and semantic relationships with other objects.

2.2 Topographic entity

Based on the previously described concepts, this paper propose the concept of topographic ontology, which is composed of a series of topographic entities with similar morphological characteristics (Fig. 1(a)). These topographic entities can be expressed using object-oriented models. Each type of topographic entity has morphological characteristics, spatial location attributes, and spatial topological and semantic relationships with other topographic entities. For example, arable land and roads are both topographic entities.

Note that topography is a very complex three-dimensional object. Topographic entities should have the following characteristics: 1) topographic entities exist objectively but are also data dependent when being expressed and modeled; mountains can be regarded as an entity; and if roads between two mountains are mapped, the roads can be extracted from the mountains and regarded as an independent entity (Fig. 1(b)); and 2) topographic entities exist objectively but also depend on scales; a tract of farmland on a large scale can be subdivided into fields, ridges in fields, and roads between two fields on a small scale (Fig. 1(c)).

3 Data and processing

3.1 Study area and data

The definition of topographic ontology is given in the previous section. This study focused on topographic model construction. Therefore, the diversity of topographic entities was fully considered when selecting the experimental areas, and the availability of data in the area was also need considered. To meet the above requirement, a 1 km^2 area in the suburb of Nanjing was selected. The area belongs to gently undulating topography south of the lower reaches of the Yangtze River. The topography of this area is significantly affected by human activities, and different topographic entities, such as farmlands, roads, canals, rivers, hills, river banks, are distributed throughout the area (Fig. 2(a)).

The data employed in this study comprises a topographic map of 1:500 scale (Fig. 2(b)). The topographic map provided elevation information required for topographic model construction. Linear features, such as vegetation boundaries, road boundary lines, and headcut boundaries, in the topographic map also provide accurate boundary information for modeling different topographic entities.

3.2 Data preprocessing

Data preprocessing is mainly focused on the topographic map. First, the topographic map is categorized into roads, farmland, building foundations, river banks, gently undulating hills, and other topographic entities according to the topographic morphological and name attributes of ground objects in the experimental area (Fig. 3). Small ground objects are removed. Information of different topographic entities that cover the study area is obtained. Attributes are assigned to each topographic entity, including the name of the land type and whether elevation information exists in the ground objects, which is necessary in the subsequent modeling process.

It should be noted that the data preprocessing needs to be completed through human-computer interaction, such as selecting vegetation boundary line according to the feature attributes, or removing some fine terrain patches that do not need considered in DEM construction. All these processes need human operation of ArcGIS software.

4 Model construction method

4.1 DEM construction of linear artificial ground objects

Artificial strip topography refers to the features that are artificially transformed or constructed in a strip shape. Artificial strip topography is characterized by man-made construction or transformation, whose shape is relatively

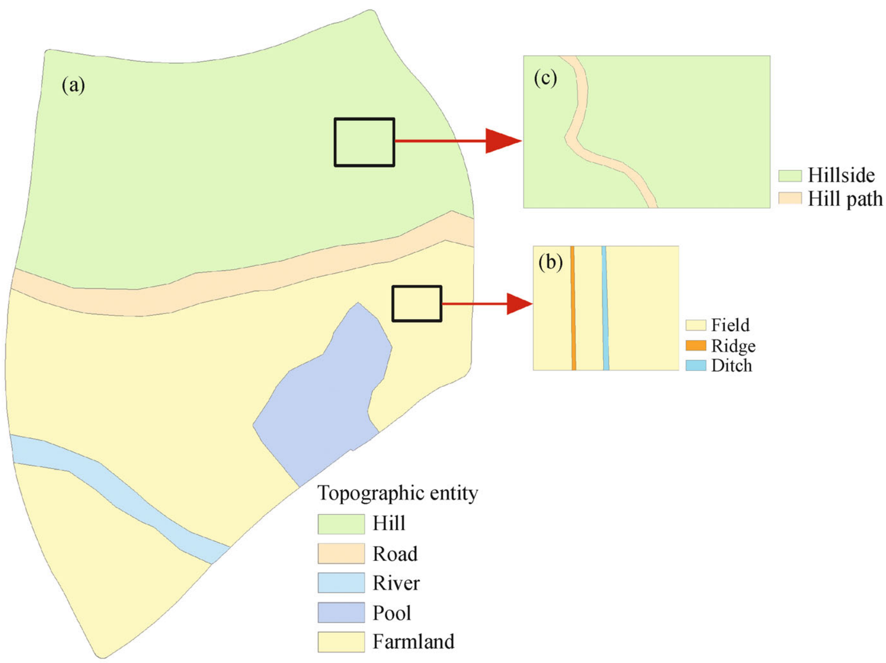


Fig. 1 Concept image of topographic entity.

(a)

(b)

Fig. 2 (a) Satellite photo and (b) Topographic image of the study area.

regular, such as roads, slopes, and ridges in fields. These types of topography have two extended boundary lines. The elevation of the boundary lines of some topographic entities, for instance, the boundary lines of most roads, can be considered the same. The boundary lines of some artificial topographic entities also have markedly different elevations, for instance, the upper and lower boundaries of slopes.

The topographic model construction process of this type of topography is described in Fig. 4. The first step is data preparation, which mainly involves the preparation of topographic boundary information and elevation information sources (Fig. 4(a)). The second step is to set a threshold and project the elevation points within the threshold on both sides of the boundaries onto the boundaries (Fig. 4(b)). In the third step, lots of new vertices are inserted into the boundary lines according to the specified step size, and the elevation values of the inserted vertices are calculated using the projected elevation values on the boundary lines (Fig. 4(c)). In this study, piecewise spline interpolation was employed for the calculation. In the fourth step, a sequence of points is emitted from one boundary line to another boundary line (Fig. 4(d)). The elevation of the generated points is

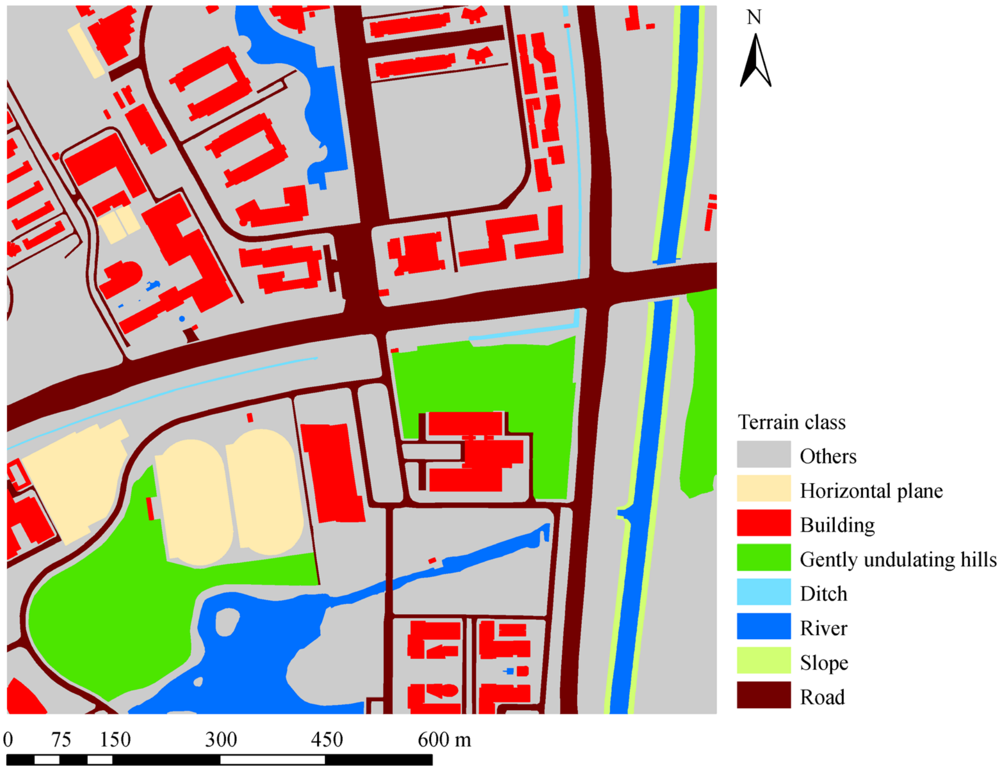


Fig. 3 Terrain classification in the study area.

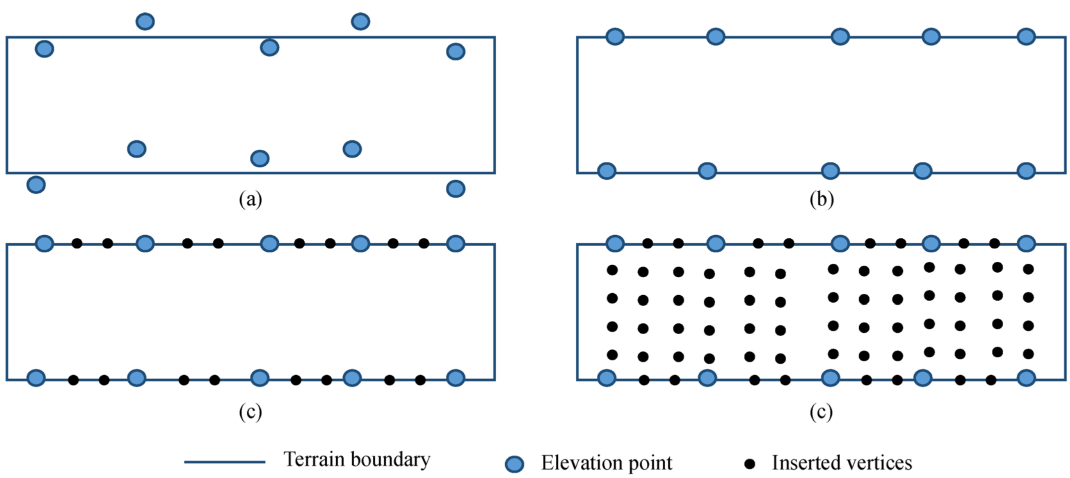


Fig. 4 DEM construction process of artificial strip terrain.

calculated based on the elevation values of the points on the two boundary lines. In the fifth step, based on the generated point set, the gridded DEMs that correspond to the topographic features are obtained by using a spatial interpolation technique.

There are two problems worth noting in the calculation process: the first problem is how to effectively address the corners of linear objects in the generation of sequences of points; the second problem is how to calculate the elevation value of the generated sequence of points by using the elevation values on both boundaries.

For the first problem, the artificial strip features described in this paper may be in the form of straight line or curve in the extension direction. When performing the encryption interpolation process described above, it is relatively simple when the strip feature is in a straight line shape, as shown in Fig. 5(a). However, spatial vacancy and vertical line anomalies may appear at the intersection, which is displayed in Figs. 5(b) and 5(c), especially the vertical line is drawn from the inner side of a curve to the

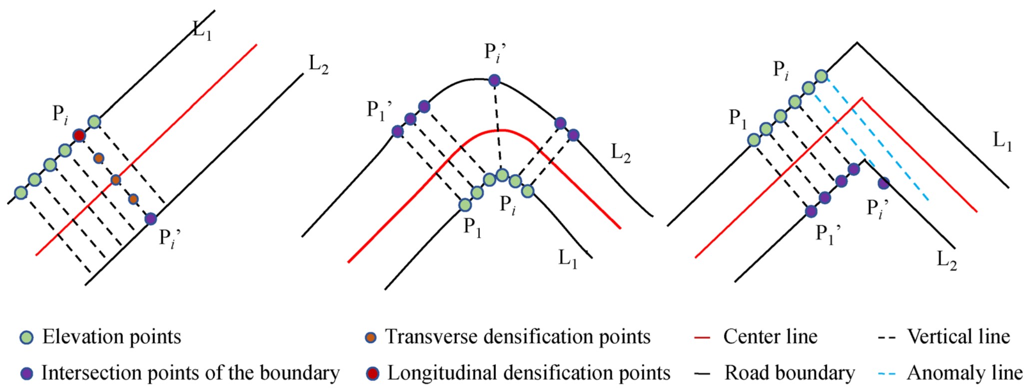


Fig. 5 Bidirectional densification and vertical abnormal line.

outer side or at a right angle (though rare). In this case, it is necessary to make an judgement according to the following two conditions whether the vertical line is anomalous or not: 1) the length of a vertical line is approximately equal to the width of the road; 2) the distance between the two intersection points on the opposite boundary line L2 is approximately equal to the step length. The anomalous vertical lines are removed, and then the corrections are subsequently made employing the following method.

First, a judgement about the inner and outer sides of the curve section should be made. Then, the outer side of the curve is densified, when vertical lines are drawn from the outer side to the inner side. If the first step is the densification of the outer side, then turn to the following step. Finally, for the normal curve, there may be intersection of the vertical line when the vertical line is drawn from the outside to the inside, so it is necessary to disconnect the vertical line at the intersection point. If the curve is a special right Angle, the inner corner point is used as a connection point, which is connected to the densified points on the outer side in the anomalous region until the vertical lines drawn from the densified points on the outer side is normal. The obtained results are displayed below in Fig. 6.

Solving the second problem, which is mainly addressed by classification according to the types of ground objects, is relatively easy. If the elevation along a cross-section in the extension direction of linear ground objects is identical, such as ridges in fields, the averaged elevation values of the points on both boundaries are assigned to the corresponding sequence of points. Otherwise, if there is a significant elevation difference along the cross-section, such as river bank slopes, linear interpolation is performed according to the elevation values on the boundaries. Since these objects are artificially reconstructed or built, the results are consistent with the true morphology of the ground objects regardless of whether the elevations are calculated as a constant or by linear interpolation.

4.2 DEM construction of planar ground objects

Planar ground objects refer to ground objects without undulations or gentle undulations within their range. For instance, sport fields and rice fields generally have identical internal elevations. Some ground objects have gentle undulations in the internal elevation and a small number of elevation points. These ground objects are treated as a planar plane, and the averaged elevation is utilized as the elevation value of the ground objects.

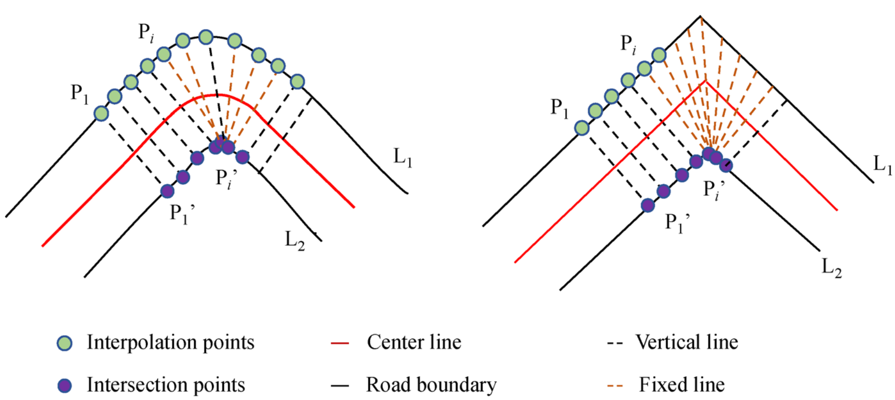


Fig. 6 Schematic diagram of treatment results of the anomalies at a road curve.

During the processing, the names of the ground objects are considered. For instance, sports fields, stadiums, and paddy fields are determined to be planar ground objects. The internal elevation is examined. If the internal elevation is a constant, the constant is applied as the elevation of the ground objects. Otherwise, anomalous elevation values, which can be removed by using a threshold of three times the standard deviation, are examined. The remaining elevation values are averaged to obtain the elevation of the ground objects.

4.3 Ground object model construction by combining semantics and spatial relationships

Some ground objects have a regular shape. However, due to their small area, no elevation points are employed for these ground objects when a topographic map is produced. At this time, the DEM can be constructed by combining the semantic information of names and the elevation information of neighboring ground objects. Typical cases in this study are the DEM constructions for ditches and ridges in fields. Here, this paper consider ditches as an example. In the study area, ditches generally refer to shallow trench-like objects between two farmlands that collect or drain water in the interior of farmland plots. Ditches are characterized by a height that is lower than farmland plots on both sides. Although no elevation point information for ditches is available, the elevation of ditches can be calculated as the minimum value of farmland elevation on both sides of the ditches minus a constant. The value of the constant can range from 0.2 to 0.5 m, which is survived in the study area and it can ensures the correct hydrological relationship of the constructed DEM. The construction principle of DEMs for ridges in fields is similar, except that the elevation of ridges is calculated as the maximum elevation of the farmland on two sides plus a constant.

4.4 DEM construction of other ground objects

Other ground objects in this study refer to ground surfaces without regular morphology and mainly consist of a natural land surface. These areas generally have continuous and irregular undulating patterns. For this type of ground object, the high-accuracy surface modeling (HASM) method was used to construct DEMs. Many studies have demonstrated that the constructed DEMs have excellent smoothness and high elevation accuracy using this method in a natural land surface environment (Yue et al., 2007; Yue et al., 2010b; Sone et al., 2012).

A surface is determined by the first and the second fundamental coefficients according to the related theorem of differential geometry surface theory (Henderson, 1998). If it assume that a surface can be expressed as $z = f(x,y)$, the first fundamental coefficients are marked as E, F, and G, and the second fundamental coefficients are marked as L, M, and N. Then the first fundamental coefficients and the second fundamental coefficients should satisfy the following Gaussian equations (Somasundaram, 2005; Toponogov, 2006; Yue, 2011):

$$\begin{cases} f_{xx} = \Gamma^1_{11} f_x + \Gamma^2_{11} f_y + \dfrac{L}{\sqrt{E+G-1}} \\ f_{yy} = \Gamma^1_{22} f_x + \Gamma^2_{22} f_y + \dfrac{N}{\sqrt{E+G-1}} \\ f_{xy} = \Gamma^1_{12} f_x + \Gamma^2_{12} f_y + \dfrac{M}{\sqrt{E+G-1}} \end{cases}. \tag{1}$$

The Christoffel symbols ($\Gamma^1_{11},\Gamma^1_{12},\Gamma^1_{22},\Gamma^2_{11},\Gamma^2_{12},\Gamma^2_{22}$) only depend on the fundamental coefficients (E,F,G) and their derivatives, and their calculation expressions can be referred to the relevant references (Zhao et al., 2014).

The above Gauss equations cannot be solved, so constraint equations needs to be constructed according to the sampling points. For each sampling point, it should fall on the surface mentioned above, then the following equation expression can be established:

$$z_i = f(x_i, y_i). \tag{2}$$

The final equations of HASM can be constructed by combining the equations formed by all sampling points with the Gauss equations, in which the unknowns in the final equations can be converted into the elevation values of fixed positions. The elevation values of the specified positions can be obtained by solving the final equations, and the DEM construction is completed at the same time. Please refer to the references for the details of the equation solution. The detailed solution process can refer to the relevant references (Zhao et al., 2014).

5 Construction results and analysis

5.1 Construction results of different objects

In the following section, the paper first analyze the characteristics of the DEMs constructed for the main terrain entities in the test area, and then discuss the modeling results from the overall perspective, as well as the advantages compared with the results from other construction methods. The resolution of DEM constructed in the research is 1 m.

1) Roads

In reality, on a cross-section of a road, the elevation is slightly higher at the center and is lower on both boundaries, and the slopes of the road fluctuate gently and change smoothly. In the model construction process, the actual shapes of roads were fully considered. The anomalous elevation points were removed to ensure that the longitudinal slope is within 3%. We obtained the model construction results. With the relief map overlapped, it can be observed that the road model construction had a smooth surface without large slope fluctuations. The morphologies of roads were complete and continuous without anomalous elevations or depressions on roads. The boundaries between two roads and other constructed objects outside roads were distinct. The overall effect is consistent with the road morphology in reality.

2) Slopes

Slopes refer to a plane with a certain inclination. There is a certain elevation difference between the top and the bottom of a slope. The surface of a slope is relatively even, and the slope changes uniformly. Based on the real shapes of slopes, we obtained the final construction results (Fig. 7(a)). The surface of the construction was smooth, and the elevation of the slopes decreased gently from the top to the bottom. The slope was reasonably connected with other ground objects without an anomalous elevation.

3) Farmland and construction areas

Farmland in the experimental area of this study consists of rice fields. The morphological characteristics of rice fields indicate that the elevation difference within a plot of field is small. Therefore, farmlands can be treated as a horizontal plane. Construction areas refer to the building foundations, which are also horizontal planes. For the two types of topographic entities, the internal elevation values were obtained, and the averaged value was applied as the elevation value of each topographic entity. The final model construction results are shown in Fig. 7. It can be observed that the construction surface and the horizontal farmland surface were even and smooth. The elevation values within each part were uniform. Distinct boundaries separate the farmland and construction areas from the constructed surrounding objects. The model construction results have a similar morphology compared with the real surface objects.

4) Gently undulating hills

In this study, gently undulating hills in the experimental area constitute topographic entities that are relatively less affected by human activities. The topographic entity has a certain elevation difference, but the elevation changes are relatively gentle. There are no traces of artificial modification. For these areas, HASM method was employed to construct the DEMs. The obtained results were smooth and even and showed certain undulating characteristics, which are consistent with the surface morphological characteristics of gently undulating hills.

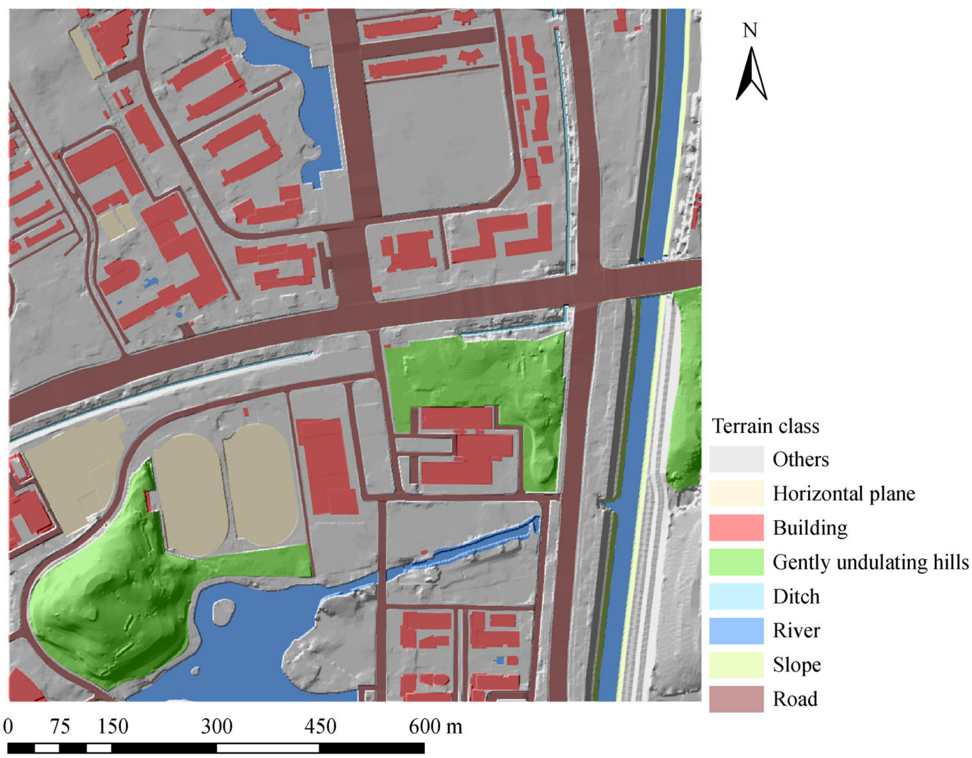
5.2 Overall result analysis

The terrain of the investigated area is relatively high. The averaged altitude ranges from 3 to 26 m. The terrain is slightly higher in the south and slightly lower in the north. The undulation of the terrain is relatively large with a certain elevation difference. In the south, the topography is dominated by hills, while the topography in the north is dominated by plains. The model construction results revealed that typical topographic features such as hills were well displayed, all types of ground objects were connected naturally, and no anomalous elevations or depressions were detected. The surfaces of roads and slopes were even and smooth, and the expression effect was detailed and intuitive, which showed the real morphologies of the ground objects. The slope map of the model construction results showed that the overall slope change in the area was small and the transition between two different types of ground objects was smooth. Areas with large slopes were mainly the junctions of rivers, ditches, and gently undulating hills with other objects. This finding is consistent with the slope characteristics of junctions, where rivers and ditches connect other surrounding objects.

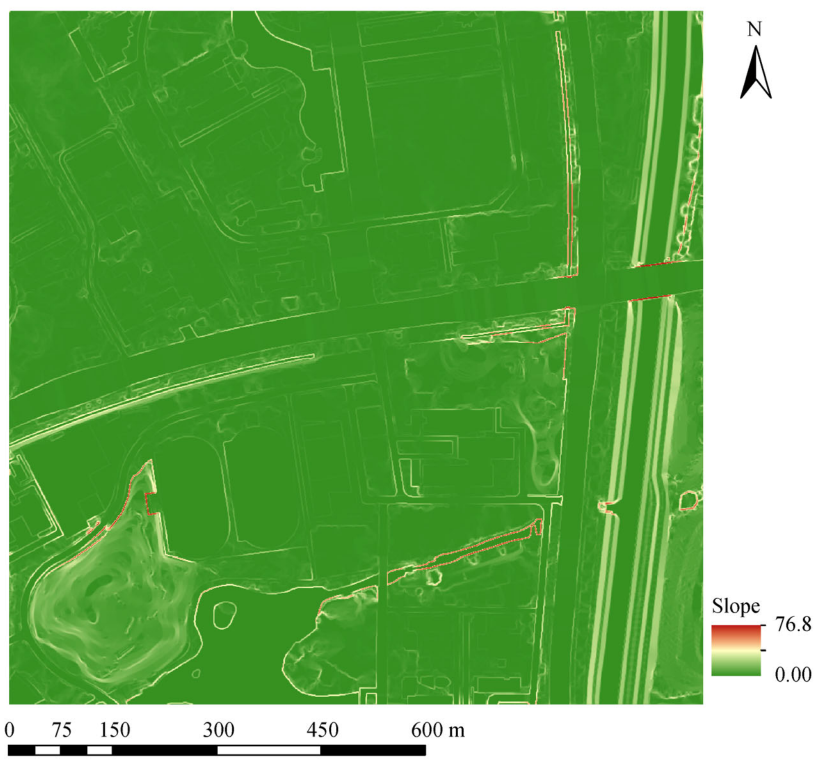
5.3 Morphological accuracy analysis

To illustrate the advantages of the method proposed in this study for constructing DEMs in human active areas, the paper employed the same data but different construction methods to construct the DEM in this section. Two types of methods were employed. The first type was an indirect construction method. In this method, elevation points and contours were utilized as the source of elevation information. Boundary lines of various types of ground objects were used as constraint lines to construct a triangulated irregular network (TIN), which was further transformed to the DEM on a regular grid. The second type of method was the direct construction method. The contour lines were discretized into scattered elevation points. The existing elevation points were synthesized as elevation data sources. Various conventional interpolation methods were used to construct the DEM. The interpolation methods were the inverse distance weighted (IDW) interpolation method and Spline with Barriers (it is abbreviated as Spline_B in this paper) interpolation method.

Figure 8 is a comparison of the relief maps generated from the constructed DEMs using different methods in the experimental area. Figure 8(a) shows the results obtained by using the TIN method in the study area. Figures 8(b) and 8(c) show the construction results after the contours are converted into points that were merged as the model points with the original elevation points and interpolated using the IDW and Spline_B interpolation methods. The land surface obtained by the TIN model construction was not smooth, which shows distinct geometric shapes. In some areas, a depression occurred due to the existence of low-value areas nearby. In the TIN surface model construction method, a linear method was applied, and curved surfaces were partially expressed as a plane, which failed to represent the real morphology of ground objects. The IDW is a spatial interpolation method that is weighted by distance, which may generate a bull's-eye effect around the observation points and produce an uneven hillshade



(a)



(b)

Fig. 7 (a) Relief image and (b) slope image of the study area.

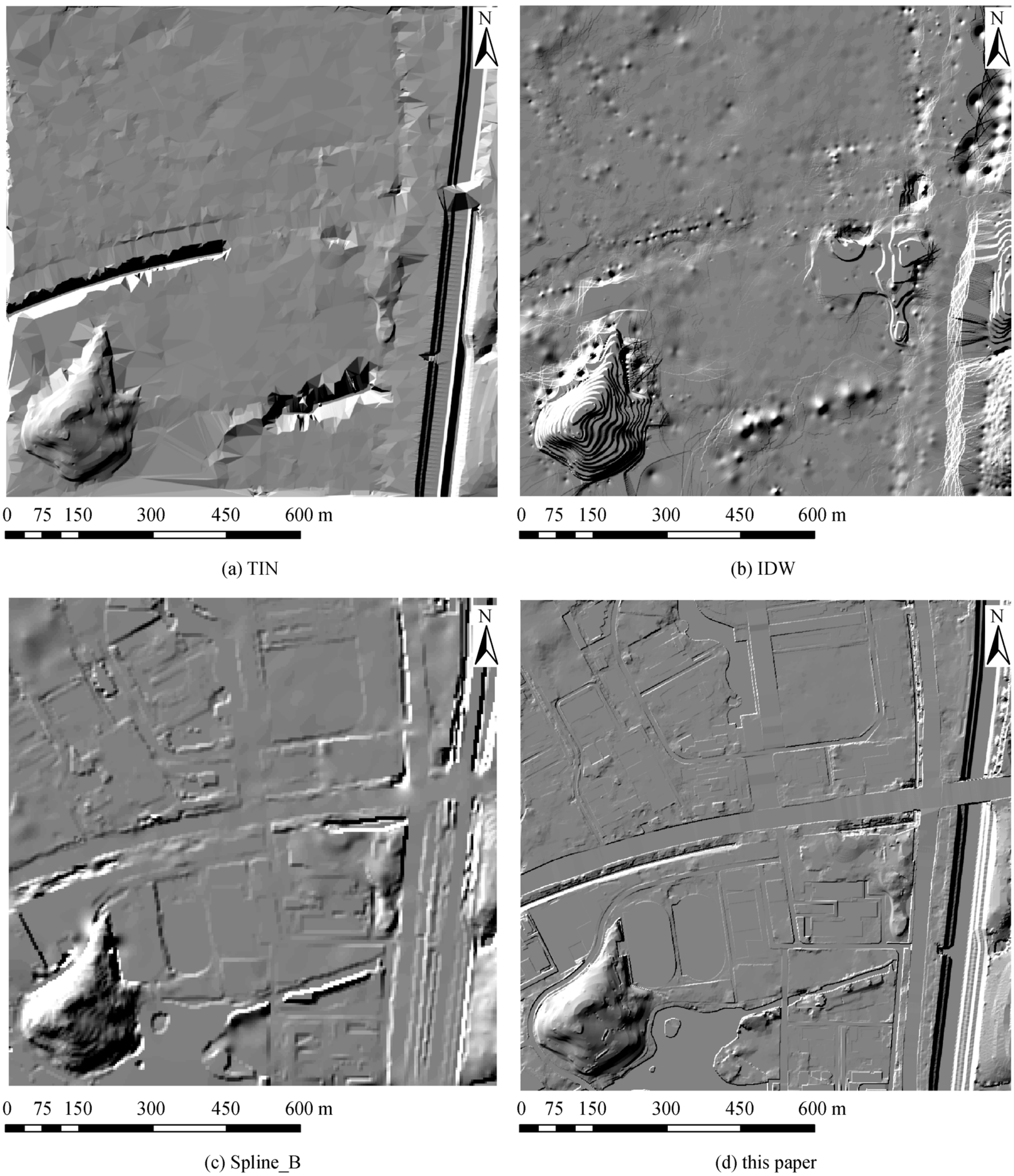


Fig. 8 Relief images of DEMs from different methods.

surface and obvious stratification in the contoured area of the hill, which yields model construction results that are very different from the real morphologies of ground objects. For the spline method, the generated DEM was relatively smooth. Although the results of the spline method well reflected the changes in the ground surface, the details of the surface morphologies were poorly reproduced. Many ellipse-like low-value areas or high-value areas were found in the constructed relief maps, which differ from the real topography.

5.4 Elevation accuracy analysis

In the previous section, the characteristics of the method proposed in this study are compared with those of conventional construction methods from a morphological perspective. In addition to the morphological characteristics, the elevation accuracy of the DEM construction structure has always been an important aspect of DEM accuracy evaluation. Therefore, elevation errors of the DEMs that were constructed using different methods were analyzed in this section. Note that the model constructions in this study model were conducted for each type of topographic entities and then integrated into a complete DEM. The DEM used a conventional regular grid, which determined that the elevation values for the boundaries of different topographic entities had a certain randomness. Therefore, the elevation verification points should be removed from the boundaries in the elevation accuracy verification. The specific range can be set to 0.5 m on both sides of the boundary lines. The boundary lines between two different entities include road boundary lines, water system boundary lines, building boundary lines, slope boundary lines, vegetation boundaries, and headcut boundaries.

The indicators employed to verify the elevation accuracy were the mean error and root mean square error. The mean error reflects the averaged difference between the DEM values and the elevation values of the verification points, which can reflect the error distribution. The root mean square error reflects the dispersion of a data set. The error indicator can be calculated as following:

$$MAE = \frac{1}{n}\sum |O(x,y) - S(x,y)|,\ (x,y) \in R^2, \quad (3)$$

$$RMSE = \sqrt{\frac{\sum \left(O(x,y) - S(x,y)\right)^2}{n-1}},\ (x,y) \in R^2, \quad (4)$$

where MAE represents the average error, $RMSE$ represents the standard deviation; $O(x,y)$ represents the observed elevation value on the verification point, $S(x,y)$ represents the elevation value on the DEM generated by different methods on the verification point, and (x,y) represents the location coordinates of the point, R^2 is the real number field.

As shown in Table 1, for the second experimental area selected in this study, the indicators of the constructed DEM using the method proposed in this study are better than those of the other methods. For example, the maximum error in the results of the method proposed in this study was 2.52 m, while the smallest maximum error was 4.01 m for the results of the other methods. The mean error in the result of our method was 0.05, while the smallest mean error among the other methods was 0.22. This finding indicates that the method proposed in this study has a distinct advantage in terms of the elevation accuracy.

To further analyze the spatial distribution characteristics of DEM errors constructed by different methods, this paper shows the spatial distribution of errors generated by different methods, as shown in Fig. 9. The error of verification points of DEMs from different methods is displayed by graduated symbols in the figure, and the symbol scheme is set the same for the convenience of visual comparison and analysis. It can be seen from the figure that compared with traditional methods such as TIN, IDW and Spline_B, the accuracy advantage of the new model is very obvious. For the DEM results of the new model, the absolute error of most verification points is less than 0.1 m. Combined with Fig. 3, it can be seen that the verification points with absolute error greater than 0.1 m are mainly distributed near roads and river slopes. The main feature of these areas is the existence of some abrupt terrain. For example, the road has a certain height subgrade, which forms an obvious height difference with the surrounding area. Because the DEM constructed in this paper is regular grid DEM, and the grid has a certain size. This kind of data structure makes the boundary of abrupt terrain unable to be expressed accurately, which will make some verification points error larger. For the traditional method, the errors in the abrupt terrain such as road and river slope are more serious, because the traditional method does not consider the individual characteristics of terrain entities, and the shape differences of different terrain entities are not considered when selecting origin elevation points in interpolation process, which could bring great errors. In addition to the above-mentioned areas, the modeling error of other areas by traditional methods is also large, which indicates that the DEM Interpolation method selected or designed for different terrain entities is rather reasonable and applicable.

6 Discussion

Generally speaking, there are several aspects to consider whether a DEM construction model is worthy of application. First, the modeling accuracy, including morphological accuracy and elevation accuracy; secondly, the model execution efficiency; finally, whether the modeling data source is easy to obtain.

For modeling accuracy, Section 5.3 and Section 5.4 have analyzed the advantages of the proposed DEM modeling method compared with the traditional modeling methods

Table 1 Elevation error statistics of research area/m

	IDW	Spline_B	TIN	This paper
Max_Error	4.01	7.32	8.88	2.52
Min_Error	0.00	0.00	0.00	0.00
MAE	0.33	0.45	0.22	0.05
RMSE	0.56	0.85	0.27	0.19

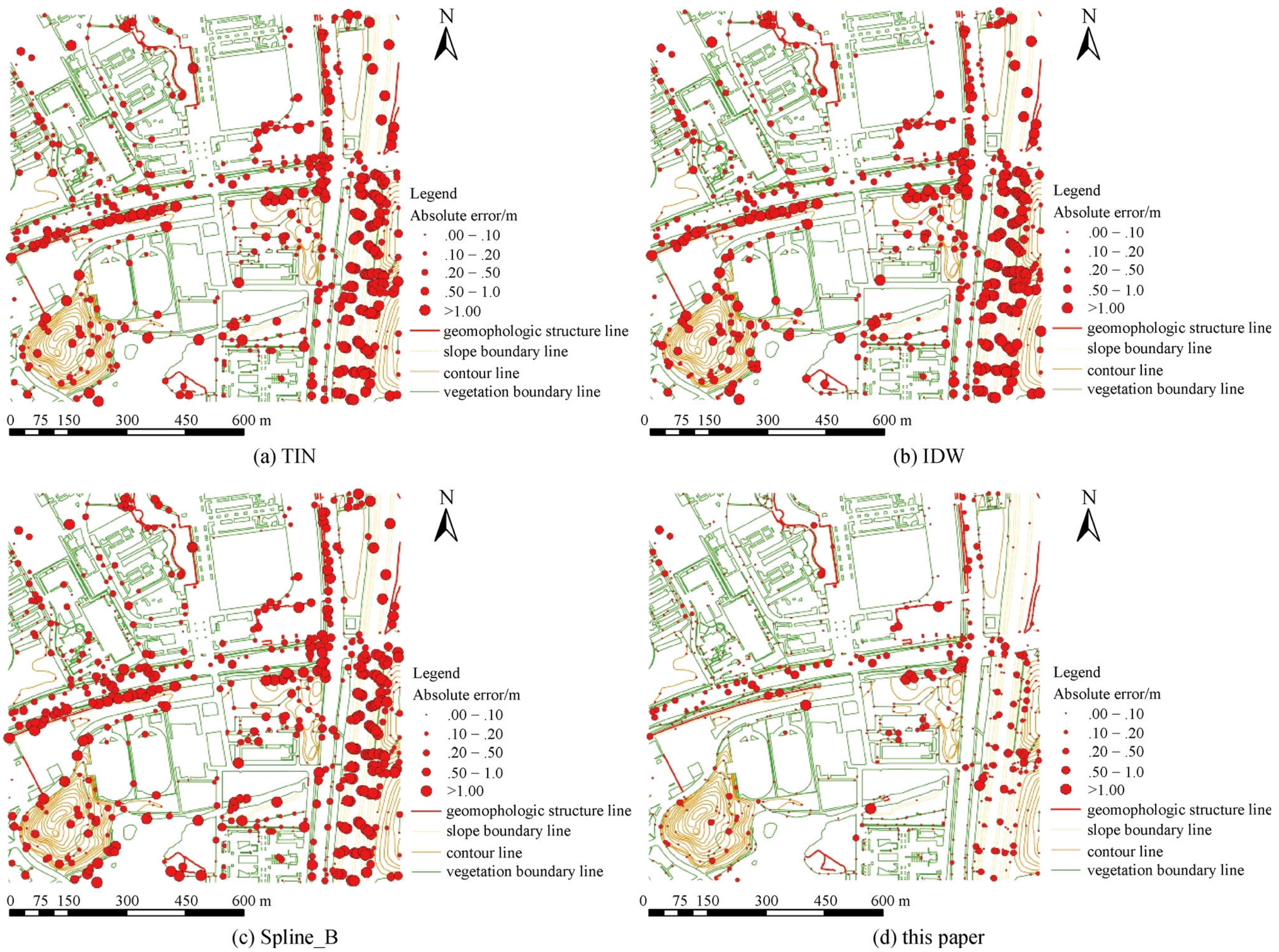


Fig. 9 Error distribution from different methods.

from multiple angles. In terms of execution efficiency, the modeling process proposed in this paper is inefficient compared with the traditional methods. The reasons include two aspects: first, the process needs a lot of human-computer interaction operations, such as various surface feature boundary line extraction, abnormal data elimination, and so on; secondly, the efficiency of some terrain entity construction methods needs to be improved, such as HASM method.

In terms of modeling data acquisition, it should note that large-scale topographic map data were employed in this study, which facilitated the extraction of boundary information of different topographic entities. This finding further demonstrates that the model construction idea based on topographic entities is feasible. However, the cost of acquiring large-scale topographic map data are high. For the generality of the method proposed in this study, it need to consider the construction of DEMs of topographic entities based on data that are relatively easily accessible, such as image and LIDAR point cloud data. This approach requires an additional step, that is, the extraction of the boundary information of topographic entities. Fortunately, researchers have carried out a large amount of research on boundary extraction of special features, especially in artificial terrains. Examples include studies based on different DEM data sources (Ortner et al., 2008), the combination of image data and DEM (Mcnally and McKenzie, 2011), using LiDAR data (Priestnall et al., 2000) to extract the ranges of artificial terrains in urban areas, and using image and LiDAR point clouds to extract feature information of artificial terrains in urban areas (Karathanassi et al., 1999; Youn et al., 2008; Javanmardi et al., 2017). Based on image data, the boundary information of an urban water network and urban bare land can be extracted (Ke et al., 2013; Palamuleni and Ndou, 2014). Abundant boundary information of topographic entities can also be obtained by using high-resolution image data to detect changes in ground objects in urban areas and extracting land use types based on different remote sensing image data (Chen and Chang, 2012; Bhaskaran et al., 2010). These studies provide references for the subsequent construction of high-accuracy DEMs based on multisource and multiscale data.

Finally, it should be noted that due to the cost of obtaining topographic map, the research area selected in this paper is small. The main purpose of this study is to verify the effectiveness and feasibility of the proposed method of DEM construction. However, the method proposed in this paper is not limited to small areas. In fact, with the government's Commission and funding, the research team of the authors had implemented a high-precision DEM construction of more than 700 km^2 in Nanjing city based on the method proposed in this paper. Of course, the DEM construction of large areas needs more data information, and the more time will be need in data preprocessing and other operations.

7 Conclusions

With the development of human society, human activities have significantly changed the surface morphology. The appearance of man-made landforms, such as roads, dams, and farmland, has increased the complexity of the topography. In this context, this paper proposed the idea of constructing a DEM with the concept of geographic ontology. The paper defined different topographic entities according to the morphological characteristics, semantic characteristics, and data acquisition of ground objects. This study then constructed elevation models for different types of topographic entities and integrated the constructed model results to obtain a complete DEM of the region. A test area in the suburbs of Nanjing was taken as an example and defined topographic entities, such as roads, river banks, farmland, building foundations, and gently undulating hills. This study focused on developing a DEM construction method for topographic entities, such as roads and river banks.

The final DEM construction effect shows that conventional DEM construction methods only utilize the elevation information of the model construction data and do not effectively fuse the semantic information and spatial relationships of the ground objects. Therefore, the constructed DEM cannot reflect the morphological characteristics of artificial landforms, such as roads, river banks, and farmland. However, because the method proposed in this study integrated the semantic information, the DEM construction results well reproduced the morphologies of various ground objects, such as the horizontal and vertical undulation characteristics of roads and the horizontal characteristics of farmland. The method proposed in this study is better than the conventional methods in terms of the morphological expression. The elevation accuracy of the constructed model results using the method proposed in this study and the conventional methods were verified at selected points. The comparison shows that the method proposed in this study has improved in terms of the elevation accuracy.

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