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Original scientific paper

Multi-Source Data Fusion Method Research on the Reconstruction and Expansion Project of Long-Line Expressway

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Abstract: At present, the application scenarios based on BIM+GIS technology are widely used in various infrastructure industries. However, in the process of 2D to 3D transformation, the application scenarios of multi-source heterogeneous data fusion in the reconstruction and expansion projects of long lines and highways have not yet been studied. This paper focuses on the reconstruction and expansion project of long-line expressway, classifies the data according to the characteristics of the project, establishes the model coding suitable for the whole life cycle, and proposes a model coding processing method based on json mapping form, which improves the maintenance of the model and coding. This paper proposes a set of data lightening methods for the whole process, aiming at data lightening for terrain and structural models with large volumes, and realizing the load lightening capability after large volumes of data enter the platform. At the same time, in order to ensure the consistency of model information data content and spatial location accuracy, a set of BIM and GIS data coupling verification method and a positioning method of coordinate system transformation between new and old structures are established. Finally, the application value of multi-source heterogeneous data fusion is verified through the reconstruction and expansion project data of a long expressway. The results show that the whole life cycle encoding mode using json mapping form improves the usability of the model and encoding. The lightweight processing of large data improves the loading capability of data.

Keywords: BIM; coordinate transformation; highway reconstruction and expansion; modal coding; multi-source data fusion

1 INTRODUCTION

At present, BIM+GIS technology is widely used in the infrastructure industry. For the reconstruction and expansion projects of long-line expressways, BIM technology has played a significant management role in engineering investigation, design, supervision, construction, operation and maintenance, and has improved the industry's fine design level, construction manufacturing and management capabilities [1]. BIM+GIS technology integrates BIM model, terrain data, GIS location data, geometric figure data, image data, oblique photography model, engineering life cycle business data and other multi-source data into the same scene through 3D visualization, laying the foundation for getting closer to the real engineering "digital twin" scene [2]. However, there are still many problems that need to be solved in the reconstruction and expansion of long-line expressways. Among them, the various data, low fusion efficiency, large volume, and old and new structural data connection, are important factors that restrict the comprehensive three-dimensional application of the reconstruction and expansion of long-line expressways. At the same time, highway reconstruction and expansion projects often need to be constructed without interrupting traffic and need to use technical means to solve the problem of interference and integration of construction organization and traffic organization.

Some scholars have studied the use of BIM+GIS technology to achieve multi-source data integration and lightweight. Scholar Sam Amirebrahimi [3] said in 2015 that in flood damage assessment, GIS technology and CityGML were used as data exchange format to analyze the impact of time-varying flood on buildings by using multi-source data. In 2018, scholar Lin Shutao [4] proposed the basic architecture of the digital twin of transportation infrastructure - the "container + service" system, which provides a feasible solution for the construction of smart highways. Vanessa Brum-Bastos [5] proposed in 2020 that the multi-source data fusion method combining MODIS data and higher spatial resolution data, combined with motion ecology, realizes the dynamic tracking of animal habitats in space and time scales. In 2020, Lu Dandan [6] et al. proposed a set of basic models for multi-source data fusion based on 3D real scene models to meet the needs of smart city construction. In 2021, Xiang Shiyao [7] et al. proposed a method of data spatial coordinate unification and data three-dimensional according to the categories and characteristics of data and realized the integration application of BIM technology and multi-source data in highway design in complex environments. In 2023, in the field of digital cultural heritage, Pamart [8] and other scholars defined a density estimation method to calculate the multi-modal enhanced fusion index, studied the complex modal layer behind the three-dimensional coordinates, and formed a three-dimensional model of data fusion by fusing all digital information related to history. Scholars such as Nica [9] reviewed the research progress of sensing technology based on deep learning and urban multi-source data in digital twin cities.

At present, relevant researches on multi-source data fusion focus on non-infrastructure industries, and tend to single point application of data fusion, result analysis and platform framework research. For multi-source data coding, data lightweight and data fusion methods for ultra-long belt projects such as highway reconstruction and expansion projects, there have not been formed studies. This paper uses BIM+GIS technology to establish a model and code conversion method between BIM and GIS applicable to the reconstruction and expansion projects of long-line expressways, proposes a lightweight method for different types of model data, and constructs a set of reusable multi-source data fusion application scheme for the reconstruction and expansion projects of long-line expressways.

2 PROJECT FEATURES

The reconstruction and expansion projects of long-line expressways are characterized by long routes, numerous types and large quantities of projects involved, including bridges, tunnels, interworking and overpasses, etc., which take a large proportion of the utilization and transformation of existing projects and require high technical standards [10, 11]. When using digital means for management, it is necessary to consider the data connection relationship between the existing structure and the new structure as a whole. The specific difficulties are as follows:

(1) The spatial connection and assembly relationship between the models of the retained part, the reconstructed part and the new part of the existing structure need to be considered.

(2) Combined with the total factor management requirements of full-line 3D BIM model, high-precision camera and reality model, under the same line length, the volume of reconstruction and expansion engineering model is huge, and the data volume and complexity are far greater than those of new expressways, and the requirements for model lightweight are high.

(3) The interference relationship between dynamic construction organization simulation and traffic organization simulation in the construction process should be considered as a whole without interrupting traffic.

(4) Need to consider the maintenance data of the existing structure, the construction process data of the new structure, and the method of transition from the construction period to the operation and maintenance period.

3 DATA PROCESSING

3.1 Data Types

In expressway reconstruction and expansion projects, business scenarios based on BIM+GIS framework involve a variety of existing and new engineering data, including unstructured data such as BIM model, reality model, and file, as well as structured data such as business class, which can be expressed by data or unified structure. According to specific data application scenarios, this paper divides data into the following five categories:

(1) Topographic data:

There are a variety of data source formats for 3D terrain, among which, the more commonly used are pts, LAS, .xyz, PCD, asc, txt format. For high-speed reconstruction and expansion projects, xyz point cloud data source is generated by extracting elevation points and contouring lines from archived CAD terrain design files for roads and terrain of existing projects that have been completed. Considering the actual operation for many years, the design alignment of the current road has changed. To ensure the matching between the existing road and the designed terrain, it is necessary to carry out full-line Lidar scanning on the existing road to obtain Las data of the existing road and the surrounding terrain. In order to improve the measurement density and accuracy, UAV and laser scanning can be used to obtain data sources containing RGB for interworking and high-fill cut edge sections.

(2) Structure BIM model data:

Structural BIM model data is generally divided into existing structural model data and new structural model data, including road model, bridge model, tunnel model, drainage structure model, foundation disposal model, traffic safety facility model and other all-factor models. It should be noted that for the structural model of expressway reconstruction and expansion, it is necessary to consider the matching and connection between the old and new models. In order to ensure that the new structure model matches the existing structure model and terrain, it is necessary to establish the model with the existing structure model as the reference. At the same time, the new model and the existing model need to perform Boolean operation with the terrain, so the terrain also needs to be established in the model format, and the final terrain model is formed after the Boolean operation with the model.

(3) GIS identification data:

The identification data includes the visual identification with correct geographical location, such as the mileage pile number, bridge and tunnel name, construction red line and key signal, which exists in the form of geometric figures such as points, lines and planes.

(4) Spatial data:

Spatial data refers to the information data used to represent the location, shape, size and distribution characteristics of spatial entities. Spatial data is rich and diverse. Besides accurate spatial positioning and matching of multi-source data, it can be further used for address matching, dynamic segmentation, path navigation, etc.

(5) Business data:

Business data refers to a collaborative management platform that helps to realize the overall control of project progress, quality, safety, measurement and documentation, optimize the organization of production factors such as personnel, materials, facilities and equipment, monitoring and monitoring, optimize the allocation of resources, operate and manage completed projects, and take GIS scenario and BIM model information as the carrier. Through web, PC and mobile APP to achieve data processing, data collaboration and file flow of engineering data. Business data is directly interactive through GIS scenarios and BI plane models. The form of data flow is shown in Fig. 1.

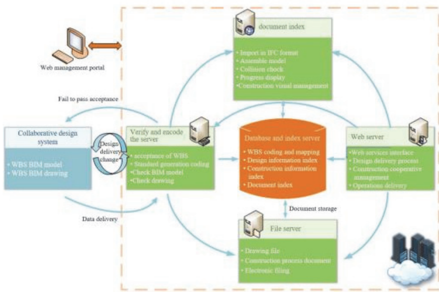

Figure 1 Schematic diagram of business data flow

3.2 Coding Method

Model coding as the whole project or a single project as a whole, according to different structures and functions, from top to bottom, from coarse to fine, from the whole to the local, step by step division. Model coding is an important identification of information transmission and component ID, a link between GIS platform and BIM model, and a unique identification code for connecting business data and structural data. Therefore, you need to ensure that each component has a unique model code. At the same time, considering the particularity of the reconstruction and expansion project, it is necessary to consider both the existing structure and the new structure. With reference to relevant specifications [12-14], the construction period and operation period of the project are considered as a whole, and the model coding classification principles are established, as shown in Fig. 2.

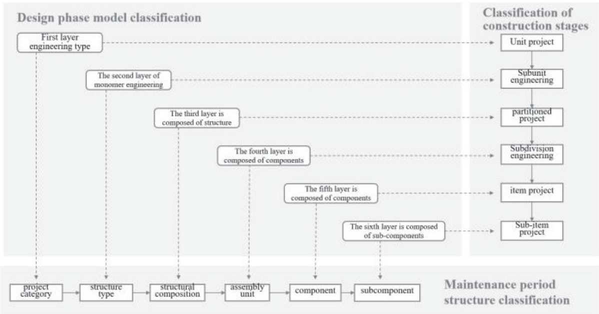

Figure 2 Coding classification principles for the whole life cycle model

For complex projects, section division, design change and construction method change in the construction process are inevitable, and the corresponding structural division also needs to be dynamically adjusted. In addition, the construction period and operation and maintenance period are not completely consistent in the division of the structure. Although coding according to the model shown in Fig. 2 can take into account both the construction period and the operation and maintenance period, it will still involve problems such as model and coding changes, merging and splitting. This paper adopts the method of mapping form in json format, that is, the mapping ID is directly used as the unique identifier in the model. The model reads the mapping ID in the mapping form through the code script, assigns the coding of the model mapping ID directly in the process of model instantiation, and then establishes the association between the mapping ID and the actual service coding (WBS/ maintenance coding, etc.) in the mapping form. What is entered in the model is the mapping ID, which is associated with the business code through the mapping form, and other attributes are attached to the GIS platform through the subsequent columns of the json form (as shown in Fig. 3).

The mapping form in json format has the following characteristics:

(1) Ensure that model components have unique coding to avoid the many-to-one phenomenon caused by the different scale of model and coding, which is not conducive to later changes.

(2) In the case of no coding split, just merge and modify, directly modify the form, without modifying the model.

(3) It is conducive to model maintenance, and the attributes can be arbitrarily expanded in the mapping form, without the need to expand in the model, and it is highly scalable and arbitrary.

(4) The data standards of BIM model and GIS platform are not the same, and direct import will cause data mismatch, loss or even damage to the source data. The unique identification code in the middle json format can be used as the "key" to ensure the integrity of the model and information and conduct verification at the same time.

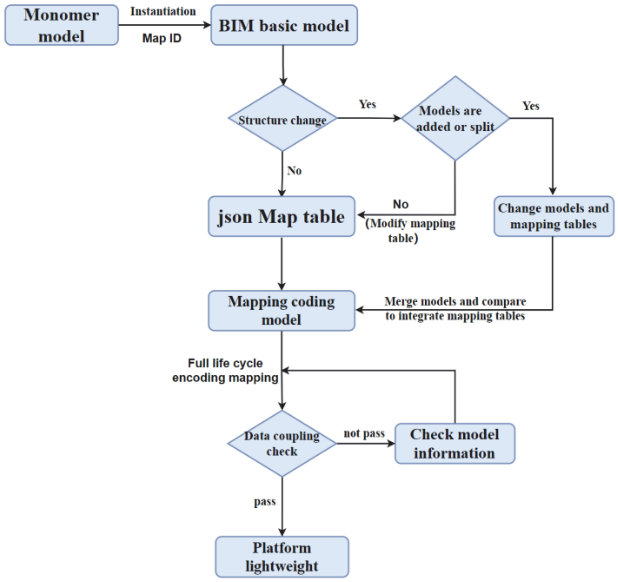

Figure 3 Model coding mapping relationship and flow chart

3.3 Data Lightweight

The low efficiency and large volume of 3D model, real scene model and high precision map are important factors that hinder the full 3D application of large projects. For the reconstruction and expansion project of expressway, it involves the connection of old and new structures, and the volume of model is doubled. Therefore, the lightweight of model data and the lightweight of loading method are the basis for the implementation of multi-source data fusion in the reconstruction and expansion project of long-line expressway.

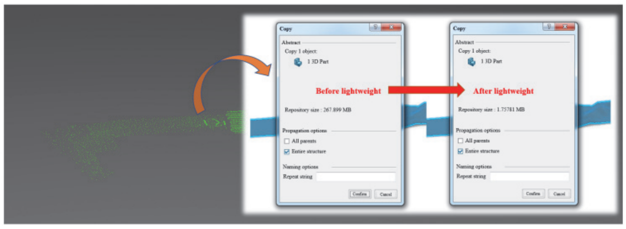

Figure 4 Schematic diagram of terrain lightweight

(1) Terrain data lightweight:

Combined point cloud data generated by existing terrain elevation points and contour data, existing road and current surrounding terrain Lidar scanning data, and UAV oblique photography data of high filled slope were used to generate terrain surfaces. Through surface repair and point cloud processing, the broken surface can be repaired to improve the topographic surface model. At this time, the obtained model cannot be used for Boolean operation with roads, Bridges and other structures, so it is necessary to grid the terrain. In the process of creating terrain Mesh surfaces, the excessive number of surfaces directly restricts the volume and loading efficiency of terrain models [15]. In order to achieve the purpose of lightweight 3D terrain model, the terrain surface was gridded, and the principle of minimum interior Angle [16] was applied to triangulate polygons through the triangular mesh area growth algorithm. According to the principle of boundary point density and distance optimization, the terrain surface was broken up and divided into multiple segments, and each subdivided terrain surface was partitioned into patch triangular mesh and optimized by adding points. The initial mesh after subdivision is smoothed by matching with the triangle of the critical segment, and the global triangular mesh lightweight terrain model can be generated by Boolean operation. Taking an interworking terrain block as an example (as shown in Fig. 4), the number of terrain triangular surfaces before lightweight is 13043953, and the volume size is 267.9 M. After lightweight, the number of topographic triangular surfaces is 340529, and the volume size is 1.76 M. The simplified proportions are 97.4% and 99.3% respectively, which reduces the volume of the model while ensuring the accuracy.

(2) Lightweight of structural model data:

Before establishing the model, it is necessary to set the topological fineness of the model according to the requirement of model precision. In the modeling process, the model occupation is reduced by the way of single structure parameterization, that is, the same type of model occupies memory only once, and will not be saved repeatedly. For example, a bridge pier, through the same cylinder, given different parameters, there are 100 piers in the model, it will be instantiated 100 times, and for the parameterized storage mode, it will be saved only once. Before the model is exported, the model is built according to the actual structure form. Taking pile foundation as an example, the model can be built according to the circle during the modeling process. In the process of export, the model can be lightweight according to the user's tolerance value by combining the triangular surface and simplifying the boundary line by the three-point method.

(3) Lightweight of platform data loading:

After the terrain is imported into the GIS platform as a model format, if it is imported as a single model without conversion, the following problems exist: terrain exists in the model format, and the terrain format that is not recognized by the GIS platform cannot add ground object information and cannot be integrated with the surrounding terrain. Although the modeling end is lightweight, the whole terrain needs to be loaded to view the local model due to the long line, and the loading efficiency is low, and there are still stuck phenomena. Unable to cover the screen, carry elevation and other information, do confluence, contour and other analysis work.

Therefore, it is necessary to transform the terrain BIM model into the standard terrain format of GIS platform. It is necessary to transform the terrain model into DSM raster data, and the analysis of raster data is an important part of GIS spatial analysis [17]. Raster data structure, also known as grid structure, is a two-dimensional matrix to express the distribution of spatial objects or phenomena of data organization. For long line high-speed projects, the corresponding DSM raster terrain is still a relatively large high-density file. If instant loading and browsing based on B/S terminal is needed, the lightweight terrain still needs to be divided and instantiated. Finally, three-dimensional slice cache (TIN format) with LOD (level of detail) structure can be generated and model cache can be loaded. It can greatly improve the BIM model browsing performance and display effect.

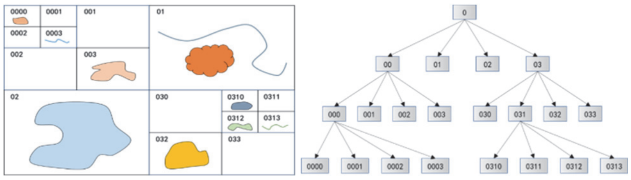

Figure 5 Schematic diagram of quadtree splitting principle

For the structural model data, quadtree partitioning type was used to encode the entire model workspace as 0, and horizontal and vertical lines were used to divide the model space into four equal parts; each part was coded as 00, 01, 02 and 03 in sequence. The divided cells are divided downward in the same way, for example, the 00th cell continues to fork downward, and the four small cells after the division are coded as 000, 001, 002 and 003. As needed, the model is divided further (as shown in Fig. 5), and the number of layers of the model partition structure depends on the number and average size of the model. Finally, the structure model data is converted into S3M spatial 3D model data format. Similarly, in order to improve the lightweight efficiency of loading, a similar method is used to convert the high-precision camera and reality model into the S3M cache file.

LOD layered loading and tile processing are the key to generate terrain, structure model, high precision camera and reality model which can be used for instant loading.

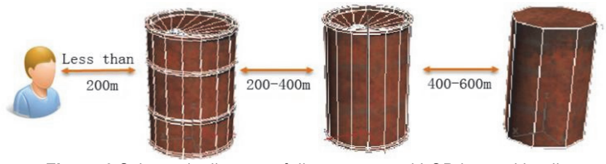

Figure 6 Schematic diagram of distance control LOD layered loading

LOD layering is to load multi-source data models with different precision for different browsing requirements. When the project overview, the distance is far from the need to load the high-precision model, load the low-precision model to release the machine performance. When focusing on a structure of concern, there are fewer models in the viewing Angle range, and the high-precision model is loaded accordingly, while the low-precision model outside the viewing area is still loaded, and added to the machine cache for call at any time. If the number of LOD levels set by the model cache is set to 3, three levels of 0, 1 and 2 are generated, of which the 0 layer is the fine layer, the 1 layer is the sub-fine layer, and the 2 layer is the rough layer. The distance represents the distance between the camera's viewpoint and the model, which determines the precision of the current scene display model, as shown in Fig. 6. Different distances show different model accuracy.

Tiling is the shredding of a single model into a large number of small files that are accessed via linked index files. Based on the scale level of the terrain pyramid of the current data, the multi-source data of each layer can be divided into blocks according to the partitioning rules, and the data of the corresponding region of each block will be stored as a slice file (cache file), so as to obtain the model cache data. As mentioned above, the partitioning type used in this paper to create a tree pyramid for cache slices is quadtree, which is suitable for spatial range data with large plane range and small height difference.

4 MULTI-SOURCE DATA FUSION METHOD

4.1 BIM and GIS Data Coupling

The BIM model is exported to the GIS platform in IFC (Interoperable File Format), and then the model cache file is generated. The geometric and semantic data is stored, queried, and exported as a GML (Geography Markup Language) file. In order to realize the complete data integration between BIM and GIS in a real sense and avoid the problems of data loss and disunity, it is necessary to conduct detailed analysis and comparison of BIM and GIS data models and coupling verification of overlapping parts.

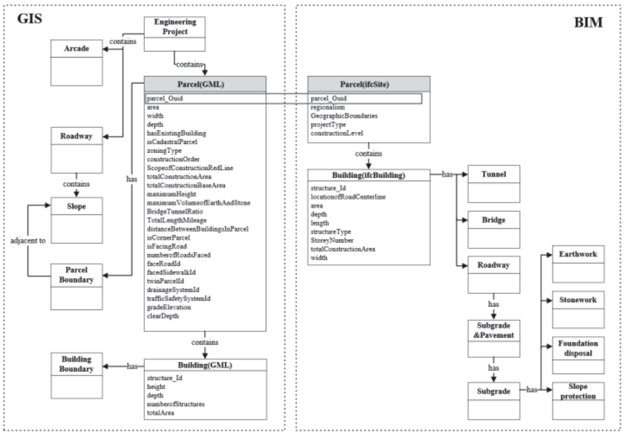

Figure 7 BIM and GIS model data coupling

For data coupling, BIM and GIS data models need to be analyzed to identify classes that are semantically similar and contain similar properties. The UML diagram of the BIM and GIS data model is shown in Fig. 7, where classes and attributes match, and classes that both exist in the UML diagram and refer to the same object are "coupling elements." To achieve semantic interoperability, data with the same meaning in BIM and GIS are coupled by using common properties (model coding). Parcel objects are located at the intersection of BIM and GIS. The Parcel objects of BIM and GIS are mapped using GUids as unique identifiers. For GML files, use the Parcel object GUID for unique identification. For IFC files, use the name of the IfcSite element. At the end of the coupling process, the Parcel object in BIM and the Parcel object in GIS are merged into a single Parcel object that contains all the information recorded separately in the IFC and GML data models. In this paper, a simple verification program is developed in Java to compare two Parcel geometries extracted from BIM and GIS to determine that they have the same geometries and positions.

4.2 Spatial Positioning

For the expressway reconstruction and expansion project, the existing structural design is completed according to the 1980 Xi'an coordinate system, and the existing maintenance model is also established according to the 1980 Xi'an coordinate system. For the reconstruction and expansion part, it is designed according to the 2000 national geodetic coordinate system. Therefore, it is necessary to carry out accurate spatial positioning and coordinate transformation for the existing structure and the new structure to ensure the accurate connection between the new and old structure models.

The conversion of the Xi'an coordinate system in 1980 and the national geodetic coordinate system in 2000 is ultimately the conversion of the reference coordinate system and the geocentric coordinate system [18]. The parameters of the two coordinate systems are not exactly the same, and the commonality is that they can be converted into space rectangular coordinate systems.

The formula for converting geodetic coordinates (L, B, H) into space cartesian coordinates (X, Y, Z) is:

$$X = \left(N + H\right)\cos B\cos L \tag{1}$$

$$Y = \left(N + H\right)\cos B\sin L \tag{2}$$

$$Z = \left[N\left(1 - e^2\right) + H\right]\sin B = \left[N \cdot \frac{a^2}{b^2} + H\right]\sin B \tag{3}$$

N is the prime unitary circle curvature radius $\left(N = \dfrac{a}{\sqrt{1 - e^2 \sin^2 B}}\right)$ of the point, a represents the long radius of the ellipse corresponding to the geodetic coordinate system, b represents the short radius of the ellipse corresponding to the geodetic coordinate system, and e represents the first eccentricity of the corresponding ellipse.

The formula for converting space cartesian coordinates (X, Y, Z) into geodetic coordinates (L, B, H) is:

$$L = \arctan\left(\frac{Y}{X}\right) \tag{4}$$

$$B = \arctan\left(\frac{Z\left(N + H\right)}{\sqrt{\left(X^2 + Y^2\right)\left[N\left(1 - e_2\right)\right] + H}}\right) \tag{5}$$

$$H = \frac{Z}{\sin B} - N\left(1 - e_2\right) \tag{6}$$

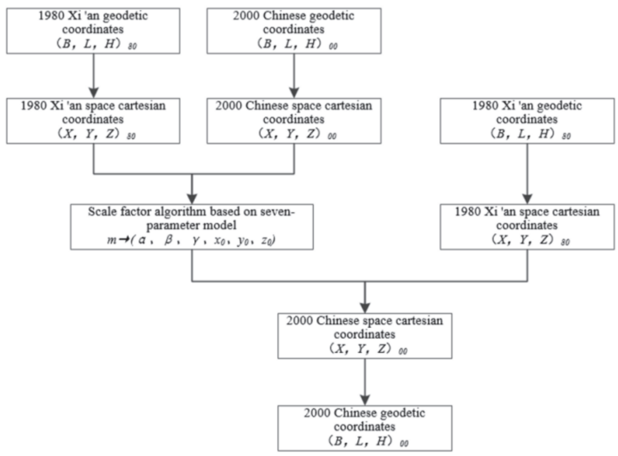

Figure 8 Flow chart of coordinate system conversion (α, β and γ are the rotation angles of the corresponding X, Y and Z axes, and x_0, y_0 and z_0 are the offsets of the corresponding X, Y and Z axes)

The process of converting the 1980 Xi'an coordinate system to the 2000 national geodetic coordinate system based on MATLAB is shown in Fig. 8. In this paper, the transformation of space rectangular coordinate system adopts the Bursa seven-parameter model [19]. The coordinate transformation model is a nonlinear function, and the Bursa seven-parameter model is solved after converting the nonlinear to linear. In order to minimize the influence of the linearity of the rotation matrix on the accuracy in the process of coordinate conversion, this paper uses the scale factor algorithm [20] based on the seven-parameter model to obtain a high-precision scale factor m by evaluating the conditions of multiple common Euconotus line segments composed of multiple reference points. The scale factor is introduced into the seven-parameter model and the remaining six parameters are obtained based on the least squares condition.

4.3 Example of Multi-Source Data Fusion

Based on the above data processing and multi-source data fusion methods, a highway reconstruction and expansion project with 220 km line length is taken as an application example to verify the results of multi-source data fusion. Taking the management of construction red line and expropriation and demolition, the simulation of traffic organization and the integration of construction organization, and the collaborative management of multi-source heterogeneous data as application scenarios, the integrated application value of multi-source heterogeneous data in the reconstruction and expansion project of long-line expressway is realized.

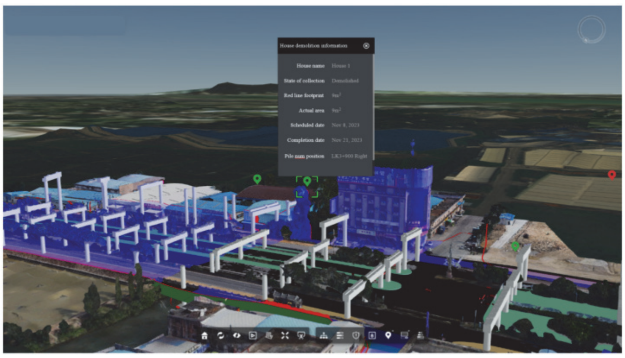

Figure 9 Application of multi-source data integration in construction red line and housing expropriation and demolition

Through the integrated application of BIM model, HD video, 3D real scene model, construction red line and regional geometric elements, and relocation GIS label, the scope of relocation is clearly defined in the form of visualization before project construction. The status of expropriation and demolition was recorded through the real scene model and GIS label, as shown in Fig. 9. The houses that have been expropriated and demolished are registered and recorded on the platform and the model is flattened. By comparing with the historical status, the visualization and fine management of the expropriated and demolished houses are realized.

In the process of highway reconstruction and expansion without interrupting traffic construction, the complex interaction between traffic organization and construction organization is solved.

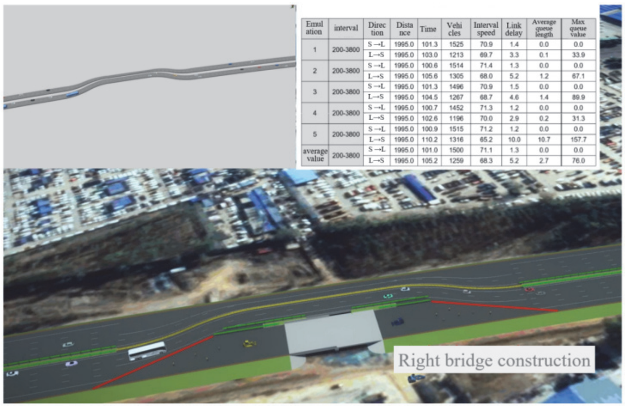

Figure 10 Integrated analysis of construction organization and traffic organization simulation

Open the interface with the traffic organization simulation software, realize the integrated simulation with the traffic organization under the condition of guaranteeing traffic flow during the construction organization process, assist the formulation of the overall construction organization plan, determine the traffic restriction and speed limit plan, and effectively reduce the traffic conflict rate and the possibility of traffic congestion. By integrating the multi-source data such as the real scene model, film and terrain, a traffic simulation and analysis visual electronic sand table that can show the real dynamic traffic flow is established, as shown in Fig. 10.

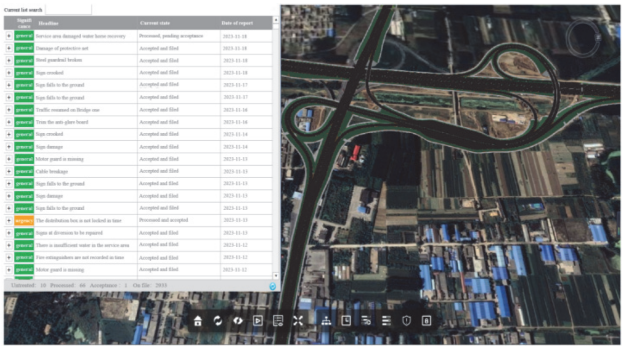

Figure 11 Collaborative management platform for long line expressway reconstruction and expansion projects based on multi-source heterogeneous data fusion

Through the fusion application of multi-source heterogeneous data, a project collaborative management platform was established, as shown in Fig. 11. Combined with the Internet, mobile terminal, big data and other technologies, the project collaborative management platform based on BIM technology and the shared management mode of full participation are established. Through real-time data collection and sharing on site, the quality of components can be traced, the safety control can be all-round, the progress can be visualized in real time, the management efficiency can be improved, the management cost can be reduced, and the information management level of project construction can be comprehensively improved.

5 CONCLUSION

(1) This article combines the characteristics of the long-distance expressway reconstruction and expansion project, classifies the data, innovatively proposes a coding

system suitable for the entire life cycle, and integrates application methods for models. Through the encoding processing method mapped by JSON forms, the maintainability, scalability, and verification capabilities of the model and encoding are improved.

(2) For the multi-source data of the expressway reconstruction and expansion project, a set of lightweight data processing methods for the entire process is innovatively proposed. This method can effectively reduce the volume of data and improve the capability of lightweight data loading.

(3) A BIM and GIS data coupling verification method and a positioning method of coordinate system transformation between new and old structures are proposed, which improves the accuracy of multi-source data fusion in expressway reconstruction and expansion projects.

(4) Based on the above work content, the multi-source heterogeneous data scenario fusion application of B/S terminal long line complex highway expansion project is realized. To realize the real-time view of multi-source heterogeneous data fusion scenario on the mobile end will be the focus of the next stage of research.

The proposed method has potential of future other AI-based applications, for example, semantic segmentation [21-31] and point cloud analysis [32, 33].

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