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AUTOMATIC SAFETY EVALUATION AND VISUALIZATION OF SUBWAY STATION EXCAVATION BASED ON BIM-FEM/FDM INTEGRATED TECHNOLOGY

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Abstract. With the progressive promotion of BIM technology in collaborative design and engineering data management, there are large amounts of project information available for intelligent construction, engineering computation and design optimization. In the construction of subway station, BIM technology is still not mature and the engineering design is generally separate from the engineering safety evaluation. Thus, this paper proposed a technology that integrates BIM and numerical simulation (BIM-FEM/FDM integrated technology) to solve the problem of separation between engineering design and computation. A three-dimensional parametric modeling of subway station excavation was first carried out using the Revit® modeling software. Afterward, a FEM/FDM-process oriented data conversion interface was developed to extract and process the critical information from the parametric BIM model for numerical simulation. Then, under the impetus of an auto-simulation interface, the safety evaluation of subway station excavation was realized automatically and visualized graphically. The research of the BIM-FEM/FDM integrated technology presented in this paper has established a supporting platform to achieve the integration of BIM-based design and safety evaluation for subway station excavation.

Keywords: deep excavation, safety, automatic evaluation, building information modeling, numerical simulation, subway station.

Introduction

The conventional design procedure for architectural engineering generally describes an actual project using independent 2D views such as plans, sections and elevations. Once one of these views is edited, all of the other views must be rechecked and updated, leading to poor documentation and possibly causing information loss and separation (Azhar, 2011). In contrast, building information modeling (BIM) is an advanced design technique with a great advantage for integrating engineering information and 3D reality and it has played an increasingly significant role in building projects involving extraordinary complexity, multipartite collaboration and sophisticated data management (Dossick & Neff, 2010; Liu et al., 2017; Pezeshki & Ivari, 2018; Porwal & Hewage, 2013). BIM technology has broken through the limitations of conventional design schemas and there is considerable potential in promoting the comprehensive utilization of parametric BIM models in the design, construction and safety evaluation phases.

In the whole lifecycle of construction projects, infrastructure design and construction safety evaluation are two significant phases, and the latter is generally implemented using numerical simulation based on a finite element model (FEM) or a finite difference method (FDM). In the traditional design schema, design and numerical simulation are commonly two separate parts, and model reconstruction is required for numerical simulation, which is cumbersome and time-consuming. Along with the rapid development of BIM technology in the construction industry, BIM-based design schemas and BIM-FEM/FDM integrated technology have become the focus of research in recent years. In bridge engineering, Jeong et al. (2017) integrated BIM technology, computation models and structural health monitoring systems into an information modeling framework. To efficiently simulate the damage patterns of buildings and building communities under the action of severe earthquakes, Ren et al. (2019) proposed

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a preprocessing procedure to convert BIM-based building and building communities to refined finite element models and thus provided a powerful bridge for structural computation models and BIM-based structures. Moreover, in pavement engineering, Tang et al. (2020) developed a conversion platform to integrate BIM-based design and pavement structural computation.

In recent decades, underground engineering has developed very rapidly in a new round of urban underground space utilization (Xu et al., 2019; Xue et al., 2015). In most cases, the construction of underground infrastructure is full of challenges owing to the complex construction environment and massive field-specific information (e.g., construction organization and geotechnical investigation information) and automatic and real-time information management and safety evaluation are generally more urgently required (Ding & Zhou, 2012; Qian & Lin, 2016). Many studies have attempted to introduce BIM technology into underground engineering. In subway engineering, research on BIM-FEM/FDM integrated technology generally focuses on conventional tunnel excavation, which is accomplished using a tunnel boring machine (TBM) (Alsahly et al., 2020; De Matteis et al., 2019; Fabozzi et al., 2021; Ninić et al., 2020, 2021; Sharafat et al., 2021). As for the construction of subway stations, it is commonly implemented using the cut-and-cover method (CCM) due to its short construction period, low cost and relatively low risk. There are some studies on the BIM-FEM/FDM integrated technology that is applied to the subway stations excavation using the CCM (Ma, 2019; Yao, 2018). In these studies, the geometric model of deep excavation was exported from Revit by a plug-in and then imported to numerical simulation software and the following steps are actually the same as traditional manual modeling and simulation. These studies have contributed to the BIM-FEM/FDM integrated technology but the process from BIM to FEM to automatic simulation and safety visualization has not been satisfactorily resolved. Besides, the use of CCM for construction of subway stations is similar to braced foundation pit excavation, in which related studies on BIM technology principally focus on the management of projects but lack numerical simulation (Lee et al., 2020; Li et al., 2018; Zhu et al., 2019). Table 1 provides some recent research on BIM-FEM/FDM integrated technology.

Consequently, this paper aims to propose a technology that integrates BIM technology and numerical simulation (BIM-FEM/FDM integrated technology) to solve the problem of the separation between engineering design and computation. The outstanding challenges in this study can be summarized as follows: (1) the complexity of systematically embedding the critical information (e.g., geometric and parameter information of engineering objects and the construction process) into a parametric BIM model so that the information can be fully utilized in the numerical simulation stage, (2) the difficulties in automatically converting the parametric model into a numerical simulation model through comprehensive consideration of the construction process and mesh generation, and (3) the challenges in processing and visualizing the simulation results to realize the FEM/FDM-to-BIM process. To resolve these challenges, the proposed BIM-FEM/FDM integrated technology is implemented with a parametric BIM model of subway station excavation using the CCM, in which the parametric BIM model includes geometric information of engineering objects, geological and geotechnical information of a digital terrain model and construction process. Then, a data conversion interface of a new object-oriented data structure based on constitutive model (CM) of the engineering objects is proposed to extract, transmit and store the digital data of the BIM model. The data conversion interface has broken the barrier of parametric modeling and numerical simulation isolation and realized the automatic mesh generation for dynamic simulation, and these problems have not been well solved in current related research. Besides, an auto-simulation interface is developed to conduct the dynamic numerical simulation that considers the construction sequence, in which generation of numerical model can be fully automated without operation and safety evaluation of deep excavation can be efficiently realized. Finally, a JSON format data structure

Table 1. Recent research on BIM-FEM/FDM integrated technology

Article type	Authors/year	Field	BIM tools	FEM/FDM tools
Journal	Jeong et al. (2017)	Bridge engineering	OpenBrIM	Not mentioned
Journal	Ren et al. (2019)	Building industry	CAD	Not mentioned
Journal	Tang et al. (2020)	Pavement engineering	Revit, PKPM/YJK-BIM, IFC	ABAQUS
Journal	Fabozzi et al. (2021)	Tunnel excavation	Bentley	PLAXIS 3D
Journal	Sharafat et al. (2021)	Tunnel excavation	Autodesk Civil 3D, IFC	Not mentioned
Journal	Ninić et al. (2021)	Tunnel excavation	Revit, IFC	IGA analysis
Conference	De Matteis et al. (2019)	Tunnel excavation	Revit	PLAXIS 3D
Journal	Lee et al. (2020)	Foundation pit excavation	3D MAX, Revit	No
Journal	Zhu et al. (2019)	Foundation pit excavation	CAD	No
Journal	Li et al. (2018)	Foundation pit excavation	IFC	No
Dissertation	Ma (2019)	Deep excavation	Revit	Midas
Dissertation	Yao (2018)	Deep excavation	Revit	FLAC 3D

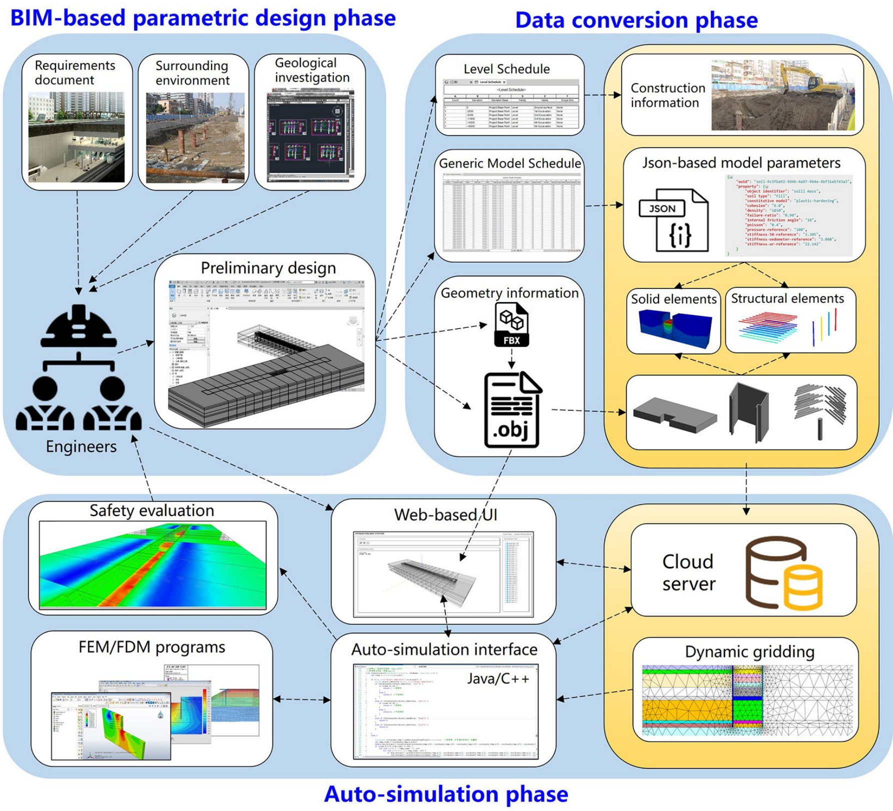

Figure 1. Overall implementation procedure for the BIM-FEM/FDM integrated technology for subway station excavation

is proposed to process simulation results and realize FEM/FDM-to-BIM interoperability. The developed BIM-FEM/FDM integrated technology can be applied to improve the interactivity of BIM modeling data in safety evaluations and effectively extend the application of BIM technology in the subway industry.

1. Overall implementation procedure

Wu et al. (2018) applied BIM technology in subway construction and proposed a method for integrating a 3D geological model and a BIM model of a deep excavation support system. Additionally, numerous finite element analyses have been conducted to evaluate the performance and safety of deep excavation of subway stations (Do et al., 2016; Hou et al., 2009; Pakbaz et al., 2013). In conjunction with the method proposed by Wu et al. (2018) and the referenced numerical simulation approaches, an overall implementation procedure for the BIM-FEM/FDM integrated technology is developed, and the flow chart is shown in Figure 1.

There are several important phases in the proposed implementation procedure, including:

- The BIM-based parametric design phase. This phase is fundamental for the BIM-FEM/FDM integrated technology but is not well resolved in existing references for the construction of subway station excavated using the CCM. A brief illustration of deep excavation of subway station with the CCM is presented in Figure 2. In this phase, a BIM-based parametric modeling method for subway station construction with the CCM is explored;
- The data conversion phase is a bridge between the BIM-based parametric model and numerical simulation, which focus on the extraction, transfer and storage of critical information from parametric BIM model and the realization of dynamic mesh generation for a geometry model based on the construction process;

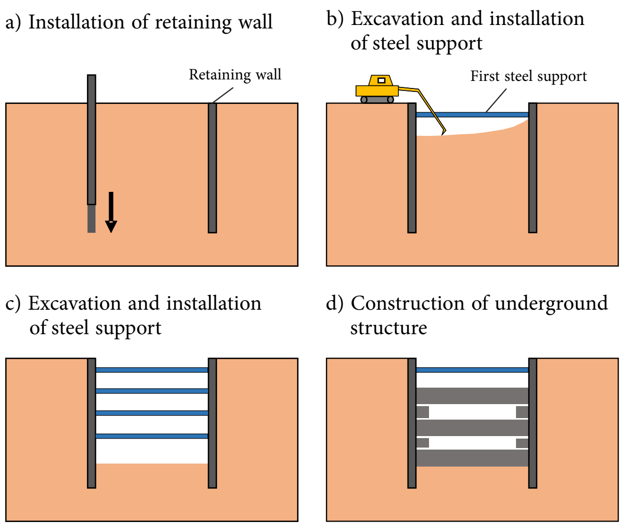

Figure 2. Brief illustration of deep excavation using the cut-and-cover method

– The auto-simulation phase is devoted to driving the process of engineering computation according to the instructions from engineers. In this phase, engineers can select target construction sections to be analyzed in the whole BIM model through a web-based user interface (UI), and then an auto-simulation interface will be used to promote the simulation process and visualization of simulation results.

In the following subsections, the details of these important phases are introduced elaborately. In this paper, a deep excavation of a typical two-floor subway station constructed using the CCM is considered as an example. The basic information for the deep excavation is schematically plotted in Figure 3.

2. Parametric modeling

In projects of the deep excavation of subway stations, the application of BIM technology can be an efficient and advanced solution to some complicated problems, such as the nonintuitive design method, the separation between engineering design and analysis and the isolation of various pieces of engineering information. However, the parametric modeling of deep excavation with BIM technology involves some issues, including the following:

– Integrating the information of soil stratification and construction process, which are within the superimposed spatial domain, into the parametric model.
– Developing an implementation method for binding the values of properties to engineering objects in parametric model.
– Prearranging the naming conventions for the properties of engineering objects, which ensures the properties can be easily identified by a parsing program to promote engineering analysis process.

In this paper, a parametric modeling method for deep excavation of subway station is presented. The parametric model is designed using Revit®, a BIM software that includes diverse tools for architectural, mechanical, electrical, plumbing and structural design and enables contributors across all disciplines to work together efficiently (Ajayi et al., 2019; Goedert & Meadati, 2008; Yan et al., 2011). Compared to traditional 2D drawings, 3D parametric modeling has the capability to produce flexible designs and provides better engineering visualization (Jung & Joo, 2011). The parametric modeling is generally based on the definition of objects which allow parametric attributes attached. A data-rich parametric model can easily be integrated with downstream applications and data interaction among these applications is easily implemented. Consequently, parametric modeling can provide great convenience for solving the separation problem between engineering design and computation.

2.1. Creation of geometric model

Geometric information is the most fundamental aspect of parametric models and should first be taken into consideration during the modeling process. In the Revit® software, a definition of a family is given to represent a group of elements with a common set of properties, called parameters, and a related graphical representation (Kirby et al., 2018). In this section, the design of geometric model is based on the Generic Model, a family template in Revit®, which allows engineers to create complex geometry.

For a typical rectangular deep excavation implemented by the CCM, soil excavation is generally advanced segment by segment. Hence, in the longitudinal direction, the geometric model can be divided into several segments with a certain width based on the actual construction process, as shown in Figure 4. In this way, the design of the

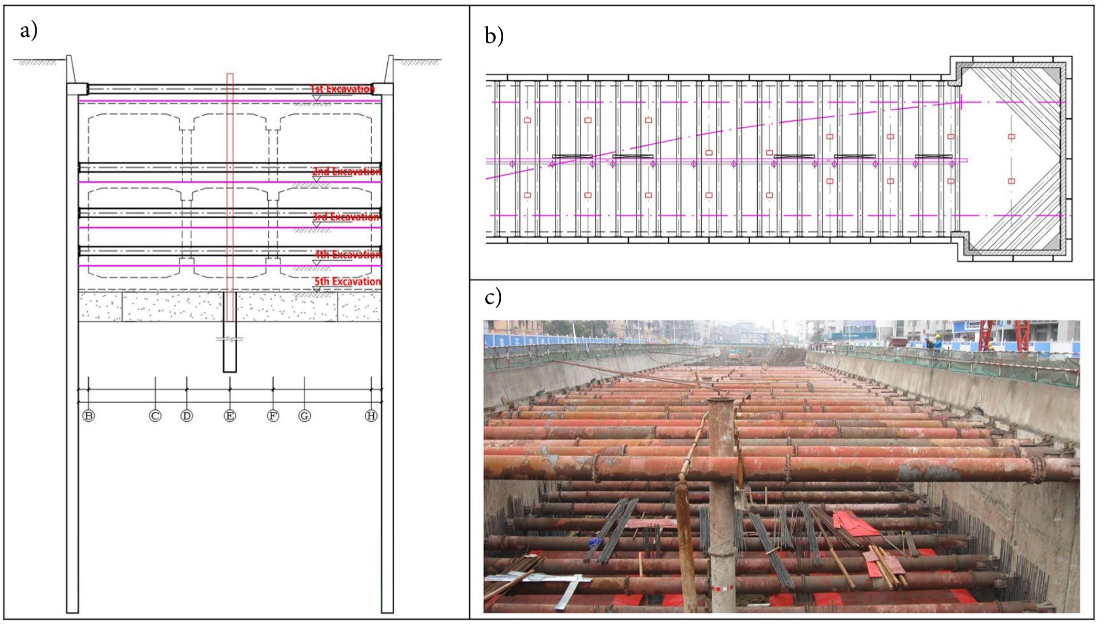

Figure 3. Basic information of the deep excavation: a – cross-sectional view; b – top view; c – site construction

geometric model is intuitive, and the model is capable of integrating construction process information, which can be utilized in the engineering computation stage.

For each segment, all the geometries can be classified as soil entities, retaining structures, etc. Considering that the determination of geometric models in numerical simulations generally refers to soil stratification, the geometries of soil entities in the BIM parametric model are divided into several layers based upon soil stratification. In this manner, the integration of soil properties into BIM parametric model also becomes much easier. Besides, in the design of the BIM parametric model, the geometries of retaining structure components should reflect the actual shapes. Figure 5 shows the design of the geometries of the retaining structure components within the scope of a standard segment.

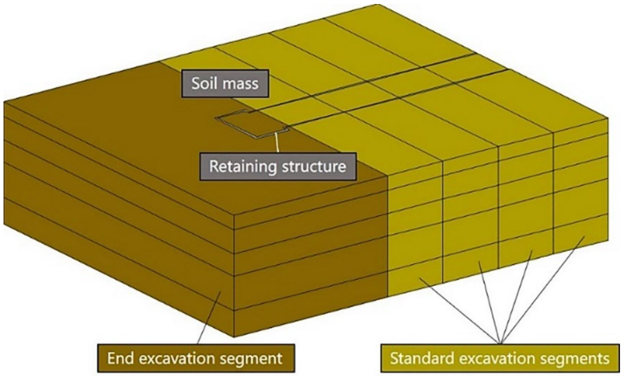

Figure 4. Design of the geometry in the longitudinal direction

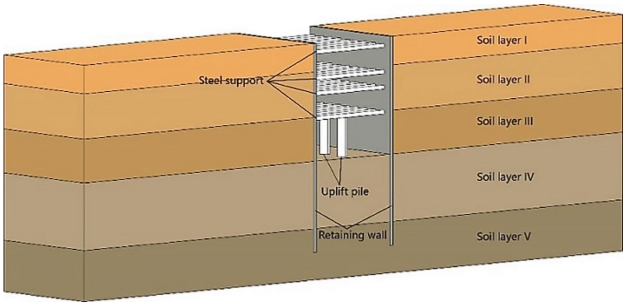

Figure 5. Design of the geometries of the retaining structure components for a standard segment

2.2. Integration of vertical excavation sequence information

The BIM-based modeling method presented in the preceding section considered the construction process in the longitudinal direction but does not account for another very important aspect of the construction process, i.e., the vertical excavation sequence information in each segment. In this section, the method for integration of the vertical excavation sequence information is introduced.

Figure 6 shows the vertical excavation sequence of the deep excavation for a typical subway station. Within the scope of each excavation segment, the excavation in the vertical direction is stratified into n stages of excavation with a maximum depth of H_{exc_n}.

In the Revit® software, the vertical excavation sequence can be expressed by a Level, which is a system family as shown in Figure 7. The vertical height of each level indicates the depth of each excavation. To gain the excavation sequence information smoothly in the safety evaluation stage, key-value pairs (KVPs) are used to store and retrieve information. Taking the keyword "1st Excavation" as an example (as shown in Figure 6), when the parsing program parses the BIM-based parametric model and detects the keyword "1st Excavation", the program will understand the usage of the value H_{exc_1} and then store the value H_{exc_1}, which can be used in the subsequent stage of safety evaluation.

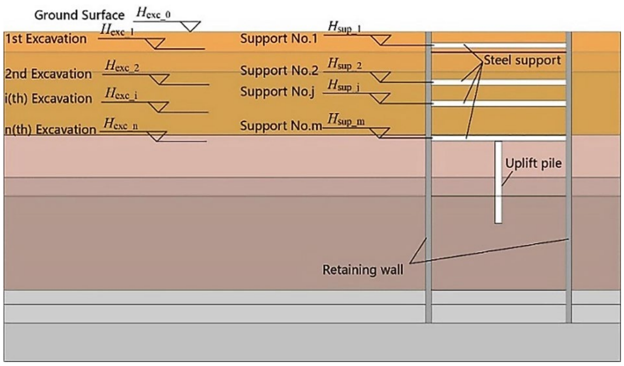

Figure 6. Vertical excavation sequence of the deep excavation of a typical two-floor subway station

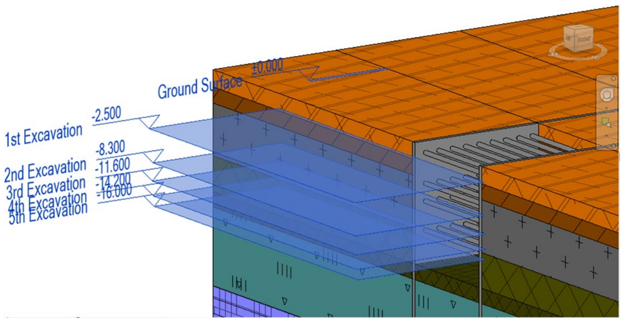

Figure 7. Expression of the vertical excavation sequence information in Revit®

2.3. Assignment of type properties

From the perspective of numerical simulation in subway station excavation, the classification of built-up members (e.g., three-dimensional solid element, two-dimensional plate/shell element, and one-dimensional beam/column/bar element, etc.) is a key step. Solid elements need to be utilized to generate mesh before numerical simulation, and structural elements are generally installed during the numerical simulation stage. The mechanical properties, which can be described by the constitutive model (CM), vary among these different elements. To drive the process of automatic simulation, the classification information and constitutive model of object need to be integrated into the parametric BIM model. In most BIM software packages (e.g., Revit®, Bentley, et al.), user-defined properties can be assigned to each engineering object. Figure 8 shows the schematic setting method of the type properties in Revit®.

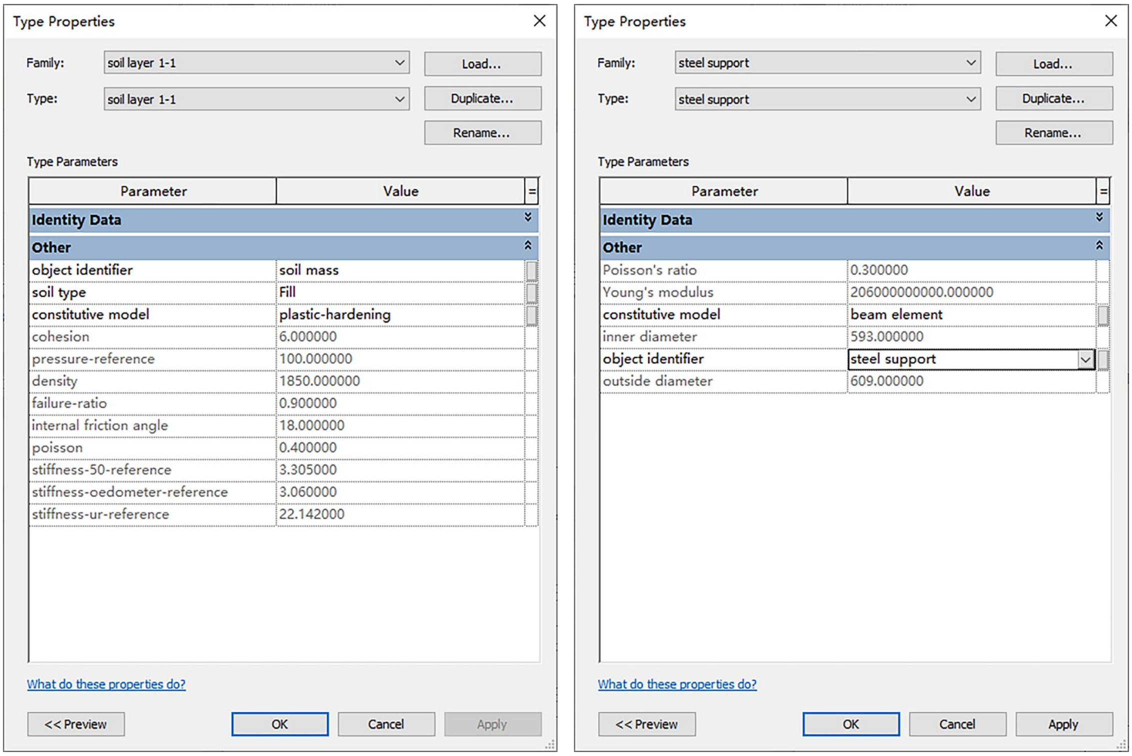

Figure 8. Schematic setting method of the type properties of the engineering objects

For the purpose of program identification, KVPs are used to store the type properties. The keyword "object identifier" is used to determine the types of objects, such as soil mass and steel support, and the selection of constitutive model in the safety evaluation stage is determined from the value of the keyword "constitutive model".

2.4. An example of parametric model

On the basis of the above parametric modeling methods, an example of parametric model is performed for an actual deep excavation project of a two-floor subway station to illustrate the practical modeling effect in Revit®, as shown in Figure 9.

3. Data conversion interface

Data conversion is an important key to the BIM-FEM/FDM integrated technology after the parametric modeling and has the ability to extract critical information from the parametric model for subsequent engineering computation. To realize the engineering computation of parametric BIM model, an FEM/FDM-process oriented data conversion interface program is developed to be capable of verifying and identifying engineering geometry information, model parameters and construction information, which are necessary for the numerical simulation software. Figure 10 presents the FEM/FDM-process oriented data conversion in the BIM-FEM/FDM integrated technology. In the proposed data conversion, the CM-based model parameters, which involves the constitutive model and corresponding parameters of all engineering objects, are firstly decoded from the parametric model and these parameters will be assigned to numerical model in the simulation stage. Then the geometric information is extracted from an OBJ file and all engineering objects are classified into solid elements and structural elements. Through the spatial position of solid elements and structural elements, the boundary condition and installation position of structural elements can be determined in the simulation stage. Besides, through the solid elements and construction information, a dynamic mesh generation method based on advancing front technique can be applied to generate the FEM/FDM mesh for simulation.

3.1. Data preprocessing for engineering objects and model parameters

Most BIM software packages have functional modules that can export the geometric information of parametric models into three-dimensional data files (e.g., OBJ files, FBX files, and DWG files). In this paper, the geometric data of all the engineering physical objects are converted to the OBJ file format, which is a geometric definition file format and flexibly compatible with various 3D geometry editing programs (McHenry & Bajcsy, 2008).

All of the model parameters can be extracted from the Generic Model Schedule. In this paper, the data of model parameters can be converted into JavaScript Object Notation (JSON) format (Afsari et al., 2017), which is a lightweight data-interchange format and easy for machines to parse and generate. Considering the importance of constitutive model (CM) of each object for geotechnical numerical computation, a CM-based data transmission and storage structure is utilized to handle the model param-

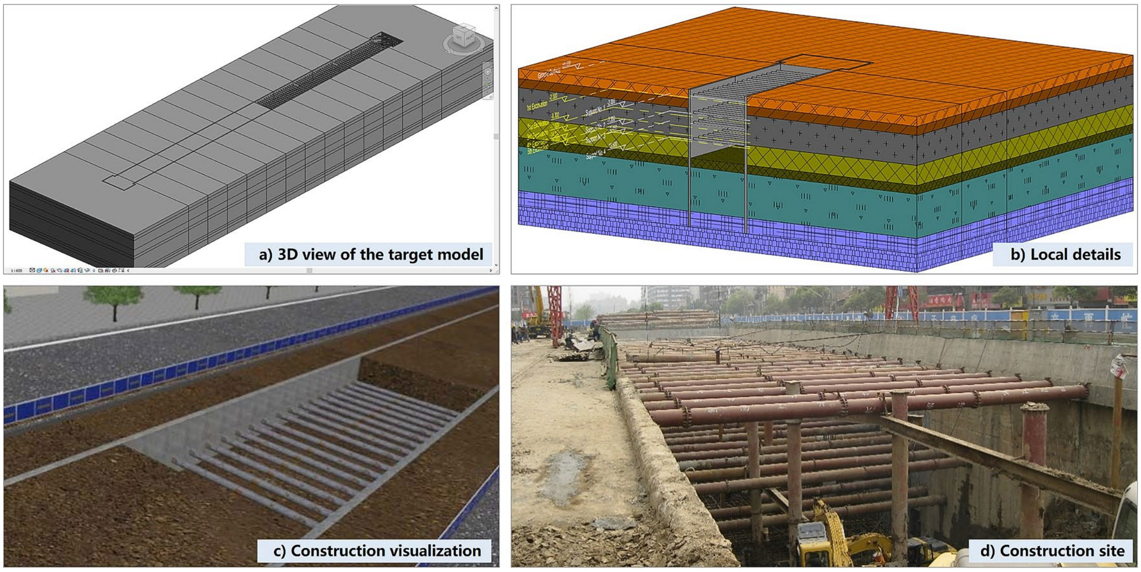

Figure 9. An example of parametric model

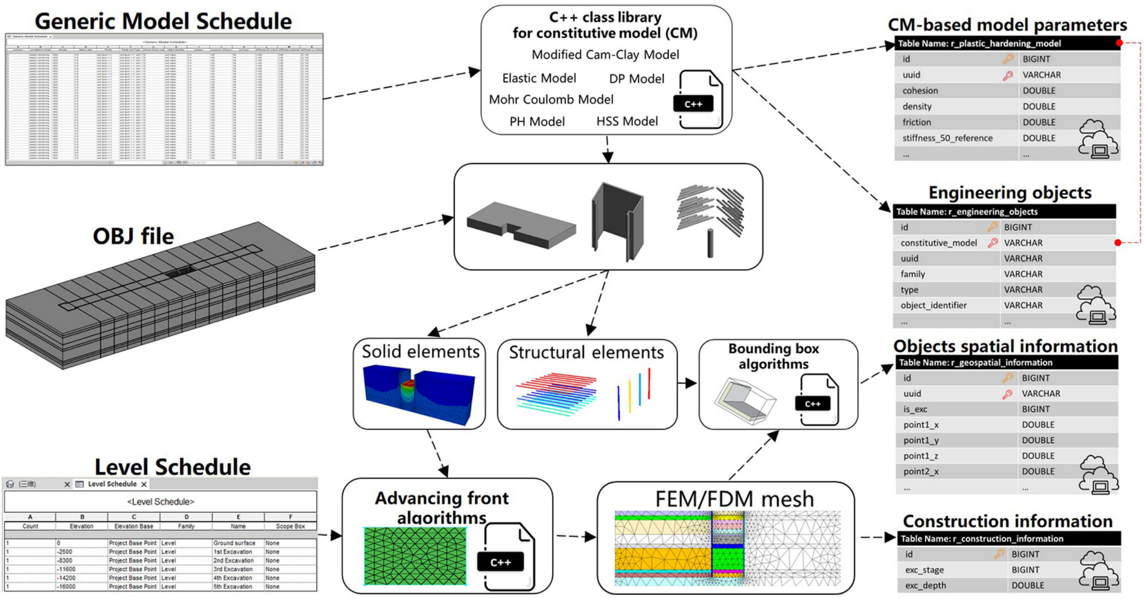

Figure 10. FEM/FDM-process oriented data conversion of the BIM parametric model

eters coming from the Generic Model Schedule, as shown in Figure 11. Additionally, to associate the model parameters to corresponding engineering object in OBJ file, a universally unique identifier (UUID) is adopted to build the relationship between them, as presented in Figure 12.

3.2. Geometry processing and dynamic mesh generation

As long as the data association between engineering objects and model parameters is built, the type of each engineering object in the OBJ file can be conveniently confirmed by a data conversion interface based upon the "object identifier". In the numerical simulation of deep excavation of subway stations, there are two main types of elements: solid elements and structural elements. Solid elements are mainly suitable for soil masses and diaphragm walls and require grid generation for geometric modeling. Structural elements primarily include beams, piles, shells and so on and can be either independent of, or coupled to, the grid representing the solid continuum. Figure 13 shows the common engineering objects in a subway station excavation using the cut-and-cover method.

Once the engineering physical objects are classified into solid elements and structural elements, geometric processing and dynamic mesh generation of the solid elements should be carried out to complete the geometric modeling stage of numerical computation. In the traditional method, mesh generation is based on the geometry of objects. This suggests that the meshes have clear boundaries at interfaces between objects. However, in the simulation process, it is very possible that excavation face will cross some grids, as illustrated in Figure 14, resulting

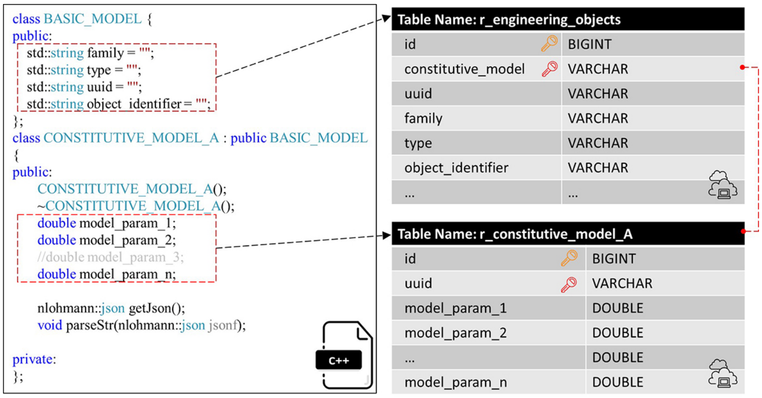

Figure 11. CM-based data transmission and storage structure

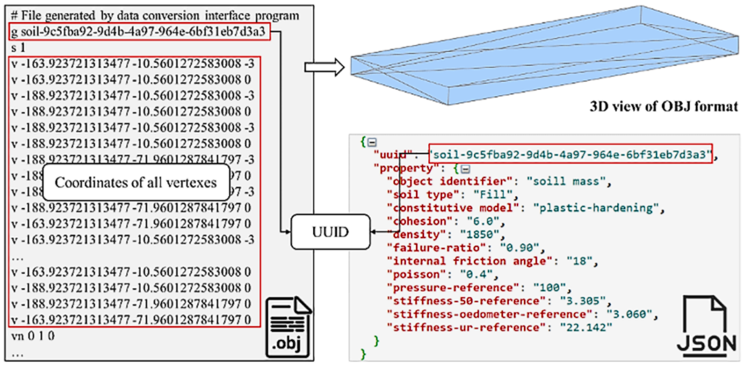

Figure 12. Data association between the engineering objects and model parameters

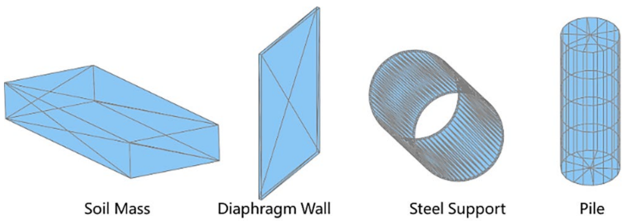

Figure 13. Common engineering objects in a subway station excavation using the cut-and-cover method

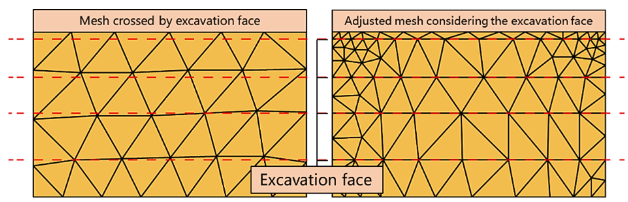

Figure 14. The situation of mesh generation in a deep excavation

in inaccurate simulation results. Therefore, it is necessary to adjust the geometry of objects based on the construction information before mesh generation.

Based on the vertical excavation sequence information obtained from the parametric BIM model, the engineering physical objects crossed by excavation faces can be easily confirmed and marked. As shown in Figure 15, each of these marked objects can be segmented into several sub-objects, which are named with a uniform "object identifier-UUID-location" format. In this uniform format, the number one is utilized to indicate the upper sub-objects.

When the geometry processing is completed, the mesh generation of engineering physical objects can dynamically take the excavation information into account. In the past decades, automatic generation of surface mesh has been continuously investigated and many algorithms have been proposed. Among these algorithms, Delaunay technique (DT) and advancing front technique (AFT) can be considered as the prominent ones (Wang et al., 2018). AFT is a greedy algorithm that generates mesh nodes from boundaries to interior gradually and executes recursively, which can generate high-quality mesh (Guo et al., 2021), and consequently it can be used in automatic mesh generation (Zienkiewicz et al., 2013). Automatic mesh generation is the key to automatic safety evaluation of deep excavation, consequently the advancing front algorithms (Löhner & Parikh, 1988; Schöberl, 1997) are adopted in this study to generate mesh, and one illustrative grid of the engineering physical objects is presented in Figure 16.

3.3. Processing spatial information of engineering objects

In the simulation process, soils above the excavation face will be excavated, and structural elements must be installed at a specified location. To realize the process automatically, the spatial information of the objects must be obtained in advance, which is a key indicator to determine whether the corresponding operation (e.g., soil

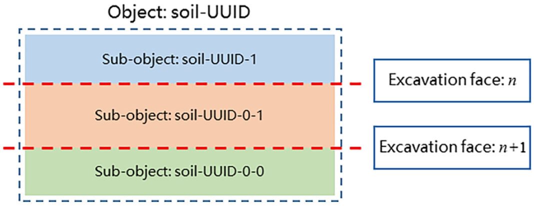

Figure 15. Uniform format of the name of an object and its sub-objects

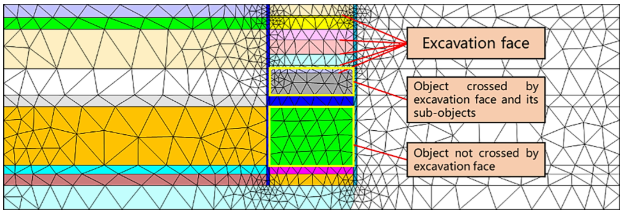

Figure 16. One illustrative grid of engineering physical objects for deep excavation

excavation, steel strut installation, etc.) should be started. In this section, the spatial information of each object is determined by an oriented bounding box (OBB), as shown in Figure 17. The algorithm to compute an optimal 3D oriented bounding box of a three-dimensional object has already been very mature (Chang et al., 2011). The vertex coordinates of the OBBs of all objects will be saved in a database and retrieved by the auto-simulation interface and the data structure of spatial information is presented in Figure 10. Through the spatial information, the boundary information of each solid element can be retrieved and then the boundary conditions of numerical model can be determined by the boundary information of all solid element. Besides, for the structural elements, taking beam elements as an example, if the center points of a beam at both beam ends obtained from the spatial information are above current excavation face, the beam needs to be installed in the current stage.

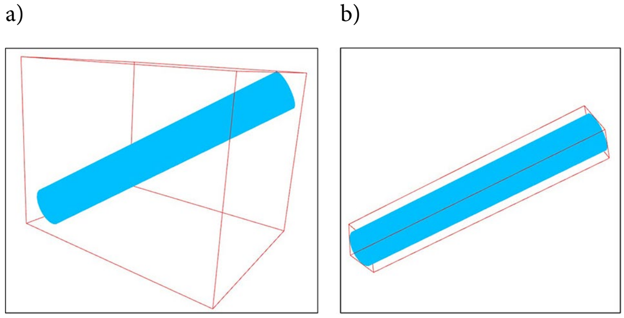

Figure 17. Common bounding box: a – axis-aligned bounding box; b – oriented bounding box

4. Automatic simulation

To implement the automatic simulation and visualization of simulation results on the basis of the previous sections, an auto-simulation interface has been developed for the BIM-FEM/FDM integrated technology, and the auto-simulation procedure is presented in Figure 18. In the auto-simulation procedure, engineers can select some target objects to be analyzed from the whole parametric model through a web-based UI. Afterwards, through the UUIDs of target analysis objects, all simulation information processed by data conversion interface will be retrieved and extracted from cloud database and the corresponding data structure of the simulation information is provided in Figure 10. The simulation information will be passed to the simulation drive and then the automatic simulation will be performed. The auto-simulation interface includes (1) the simulation drive, which mainly processes the simulation information for numerical computation and promotes the simulation of numerical simulation program; (2) results processing, a functional module to monitor whether there are simulation results to be received and to realize the visualization of the received results.

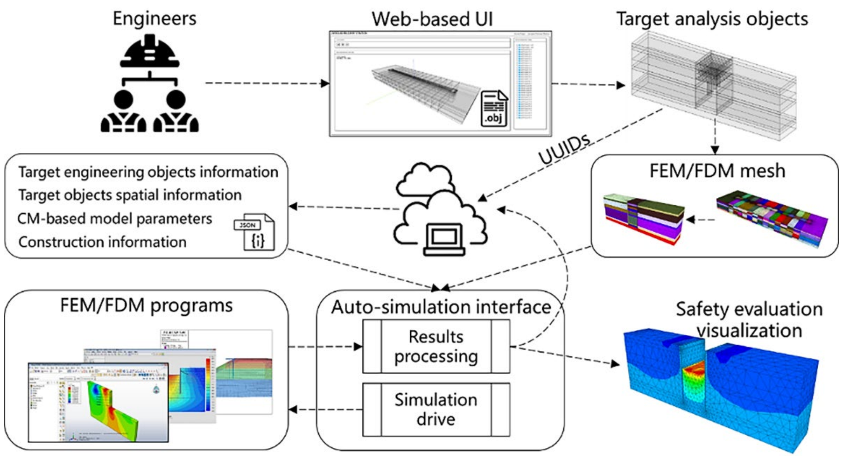

Figure 18. Implementation of the auto-simulation procedure

4.1. Method for automatic simulation

Generally, most FEM/FDM software applications provide modeling methods of command streams or embedded programming languages. For example, FLAC^{3D} provides the FISH language for simulation, which is a built-in scripting language allowing the user to interact with and manipulate FLAC^{3D} models, and ABAQUS/PLAXIS provides a command stream or Python script for simulation. Consequently, by automatically generating modeling script, the auto-simulation of subway station excavation becomes possible. In this section, the method for automatic simulation in the BIM-FEM/FDM integrated technology is introduced.

When the target analysis objects are determined, the corresponding simulation information will be passed to the simulation drive. Figure 19 presents the data processing flow in the simulation drive, which is accomplished with the C++ language. Figure 19a provides the corresponding simulation information processed by data conversion interface. The numerical simulation of deep excavation generally consists of two distinct phases: the initial and construction phases. In the initial phase, the target engineering objects information, including the constitutive models and element types of the objects, is retrieved and extracted from cloud database. Then the target objects are traversed to check whether the current object is a solid element. All solid elements will be assigned with the CM-based model parameters and the boundary conditions will be determined by the spatial information of solid elements, as shown in Figure 19b. In the construction phase, the list of excavation depths in descending order is extracted from the construction information. When the minimum height of the solid element of soil layer is less than current excavation depth, it will be removed in current stage to simulate the excavation behavior. As for structural element, if its minimum height is less than current excavation depth, it will be installed in current stage, as shown in Figure 19c. Through the data processing flow, modeling scripts will be generated to promote the auto-simulation process. Additionally, several scripts, which are used for exporting simulation results into a specific file in JSON format, will be implanted in the modeling scripts to visualize the simulation results.

4.2. Processing of simulation results

In most numerical simulation software packages, the meshes of geometric model are composed of a large quantity of zones, each of which is a closed geometric domain, as shown in Figure 20. In this study, the geometry of each zone is a tetrahedron, which has four vertices, and the simulation results will be described by the zone and its vertices. For example, the zone itself can describe the simulation results of stress, and its vertices are able to describe the simulation results of displacement. As mentioned in the previous section, the scripts, which are used for exporting the simulation results into a specific file in JSON format, have been implanted in the modeling scripts, and Figure 21 shows the data structure of the JSON format for exporting the simulation results.

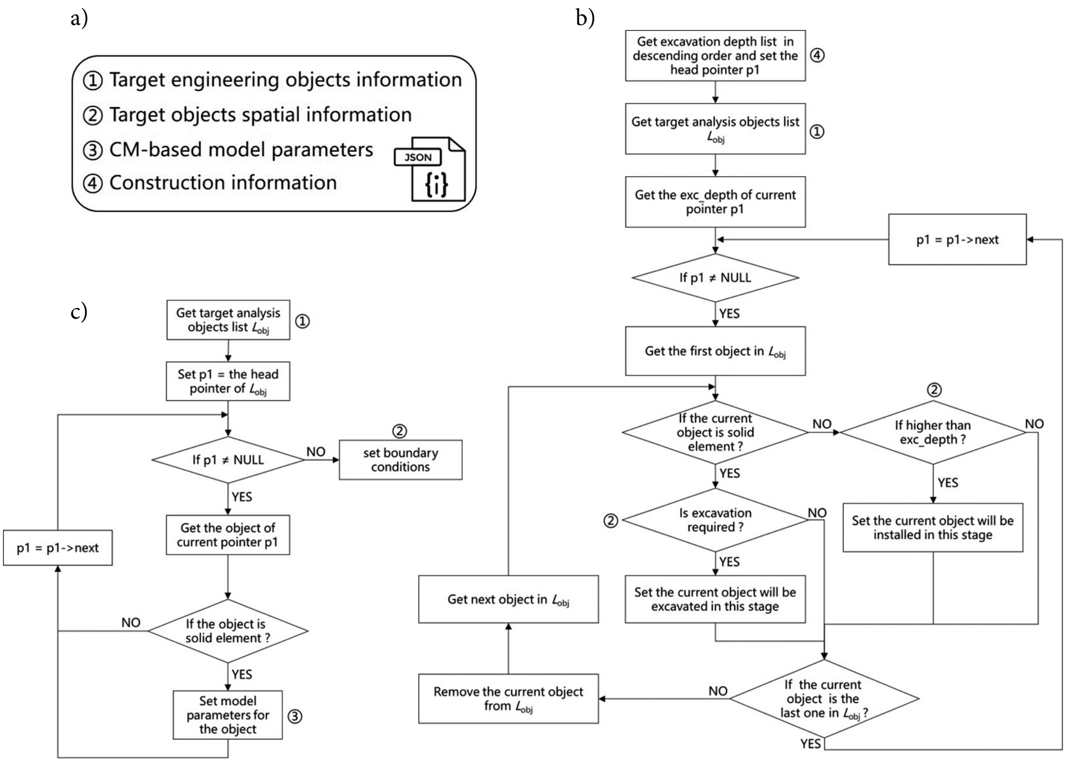

Figure 19. Data processing flow in the simulation drive: a – necessary numerical simulation modeling information in the simulation drive; b – setting of the initial conditions; c – implementation of the construction process

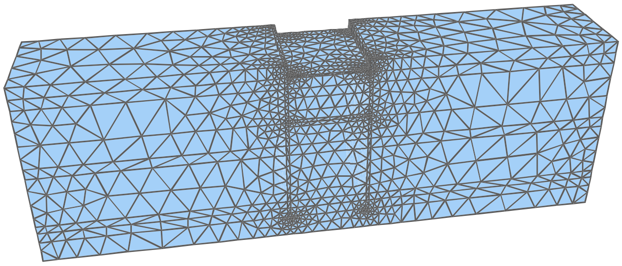

Figure 20. Meshes of geometric model

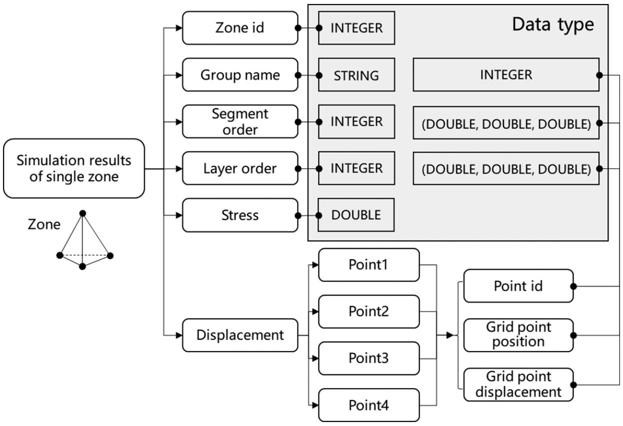

Figure 21. Data structure of the JSON format for exporting the simulation results

The JSON format for the simulation results involves the stress of each zone and displacement of each grid point. In the exported simulation results, the "zone id" is the unique index of a zone, the "segment order" represents the excavation sequence of excavation segment, and the "layer order" expresses the vertical excavation sequence of excavation segment. In this format, the simulation results for each segment at each excavation state can be stored and accessed expediently. Figure 22 presents the process of data storage and visualization of the simulation results, which is accomplished with the Java language.

5. Application of the BIM-FEM/FDM integrated technology

5.1. Background of case project

In this study, a typical deep excavation project for a subway station using the cut-and-cover method is adopted to illustrate the realization of automatic safety evaluation based on the BIM-FEM/FDM integrated technology. The parametric modeling method for a deep excavation was introduced in the previous section, and the practical BIM modeling outcome of the project was shown earlier in Figure 9. The dimensions of the whole parametric BIM model are 465 m × 144 m × 48 m. The deep excavation is approximately rectangular with dimensions of 359.00 m (length) × 20.07 m (width) × 16.00 m (depth), and the diaphragm wall is installed at a depth of 42.4 m. Along the longitudinal direction of the parametric model, there are 15 construction segments, including 2 end segments and

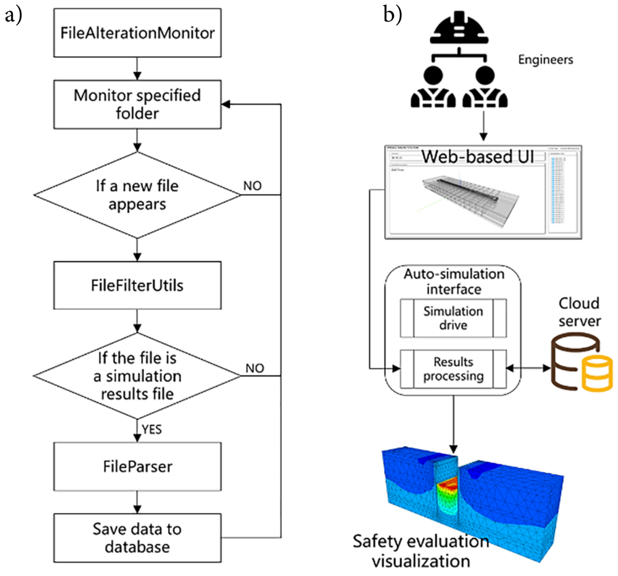

Figure 22. Process of data storage and visualization of the simulation results: a – data storage of the simulation results; b – safety evaluation visualization

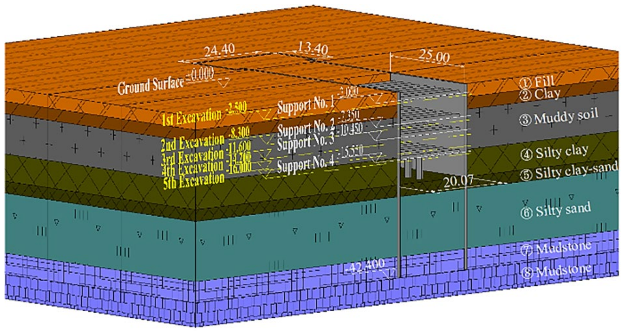

Figure 23. Basic information for the deep excavation case

13 standard segments. Within the scope of each excavation segment, the soil excavation in the vertical direction includes 5 stages with a maximum depth of 16.0 m, as presented in Figure 23.

The construction site of the deep excavation is part of the first alluvial terrace of the Yangtze River and Han River, where the soil layers are soft and the stress-strain behavior of the soils is complicated. Table 2 summarizes the soil layers determined from an in situ soil investigation. The plastic-hardening constitutive model (Schanz et al., 1999) is selected to characterize the stress-strain behavior of the soil layers ① to ⑥, while the Mohr-Coulomb model is adopted for the soil layers ⑦ and ⑧. The parameters associated with the constitutive models are also presented in Table 2.

The support system for the deep excavation includes a reinforced concrete diaphragm wall and horizontal steel props with a horizontal distance of 2700 mm. The properties of diaphragm wall are shown in Table 3. The steel props are steel pipes (for end segments: 800 mm in outer diameter and 16 mm in thickness, while for standard segments: 609 mm in outer diameter and 16 mm in thickness). Young's modulus and Poisson's ratio of the

Table 2. Basic parameters of the soil layers

Layer	①	②	③	④	⑤	⑥	⑦	⑧
Thickness (m)	3	2.8	9.2	6.2	2.7	13.7	2.1	8.3
γ (kN/m^3)	18.5	19	17.9	19.3	19.4	19.4	25	25
φ (°)	18	20	22	25	28	28	35.8	35.8
c (kPa)	6	20	14	15	3	0	0.29	0.29
E (MPa)	–	–	–	–	–	–	80	200
E_{s1-2} (MPa)	3.6	4.7	3	4.8	5	14	–	–
P_{ref} (kPa)	100	100	100	100	100	100	–	–
E_{50}^{ref} (MPa)	3.305	4.568	3.06	7.862	5.886	15.26	–	–
E_{oed}^{ref} (MPa)	3.06	4.23	2.55	6.24	5.45	15.26	–	–
E_{ur}^{ref} (MPa)	22.142	34.72	26.285	52.678	58.86	61.04	–	–
R_f	0.9	0.91	0.72	0.68	0.89	0.9	–	–

steel props are 206 GPa and 0.25, respectively. The uplift piles (from –16.00 m to –28.00 m) are reinforced concrete bored piles with a diameter of 1000 mm and a horizontal distance of 5400 mm, and Young's modulus and Poisson's ratio of these piles are 30 GPa and 0.2, respectively. The linear elastic constitutive model is utilized to represent the mechanical behavior of the diaphragm wall, uplift piles and steel props, which are modeled as solid elements, pile structural elements and beam structural elements, respectively.

5.2. Safety evaluation of deep excavation

With the parametric model built in the BIM software based on the procedure in the previous section, engineers can export the OBJ file, Generic Model Schedule and level schedule from the BIM software and upload these files to the BIM-FEM/FDM integrated platform, which provides

Table 3. Properties of the diaphragm wall

Property	Unit	Value
Thickness	mm	800
unit weight, γ	kN/m^3	25
Elastic modulus, E	GPa	31.5
Poisson's ratio, ν	–	0.2

the data conversion interface as presented above. The engineers can select the engineering physical objects to be calculated on a graphical user interface using a frame selection function, as shown in Figure 24, and then confirm the constitutive models and the construction stage for the selected objects, as depicted in Figure 25. Once these steps are completed and submitted, the auto-simulation interface will promote the safety evaluation process.

5.3. Visualization of safety evaluation and results verification

Once the numerical simulation is completed, the simulation results will be saved in a cloud database. Based on WebGL technology, the simulation results can be converted into contour figures to intuitively present the engineering safety status. In this section, the ground surface settlement and diaphragm wall deflection, which are the key indicators for evaluating the safety and stability of a deep excavation, are focused on to visualize the safety evaluation.

The contour figure of the ground surface settlement and its curve at each excavation step obtained from the BIM-FEM/FDM integrated platform are shown in Figure 26a and Figure 27, respectively. The contour figure of the diaphragm wall deflection and its curve at each excavation step are shown in Figure 26b and Figure 28, respectively.

To verify the results of numerical simulation, a simulation case that is implemented by traditional manual method is adopted in this study. The construction scheme and

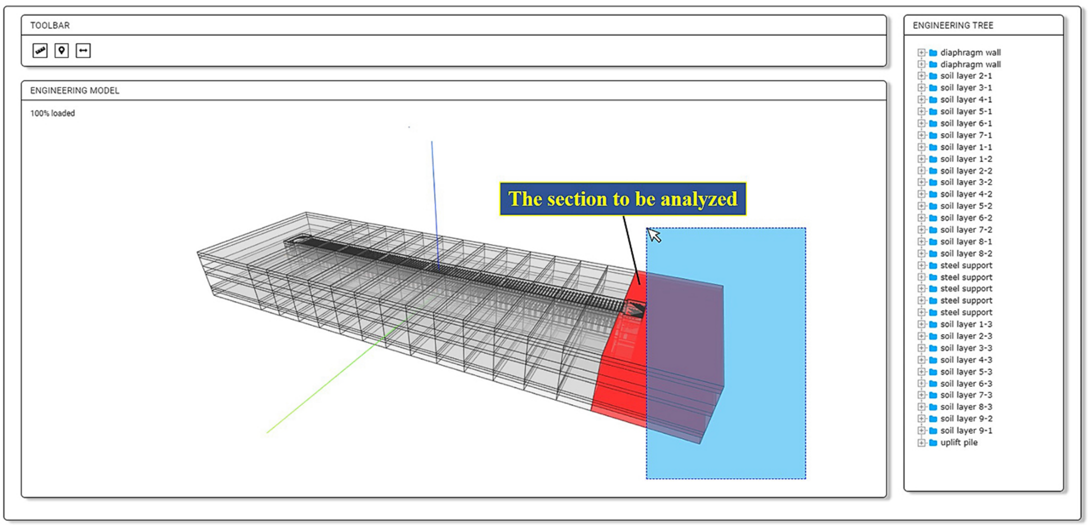

Figure 24. Selection of the target objects on a graphical user interface

model parameters of the traditional manual simulation are exactly the same as the simulation performed by the BIM-FEM/FDM technology. The corresponding simulation results are shown in Figure 29, which illustrates that the simulation results from the BIM-FEM/FDM method are in good agreement with those from traditional manual method. Consequently, when the constitutive models and corresponding model parameters are properly selected, BIM-FEM/FDM integrated technology can provide the same reasonable results as the traditional numerical simulation methods.

Besides, the observed results and the semiempirical method proposed by Kung et al. (2007) are adopted to compare with the simulation results, as shown in Figure 29. The ground surface settlement profile proposed by Kung et al. (2007) can be expressed as Eqn (1). Although the maximum wall deflection from the simulation is large than the observed results, the depths where the maximum wall deflection occurred are close. Hence, the constitutive models and corresponding model parameters can be further optimized. For the deep excavation in special stratum, some studies (Chheng & Likitlersuang, 2018; Dong

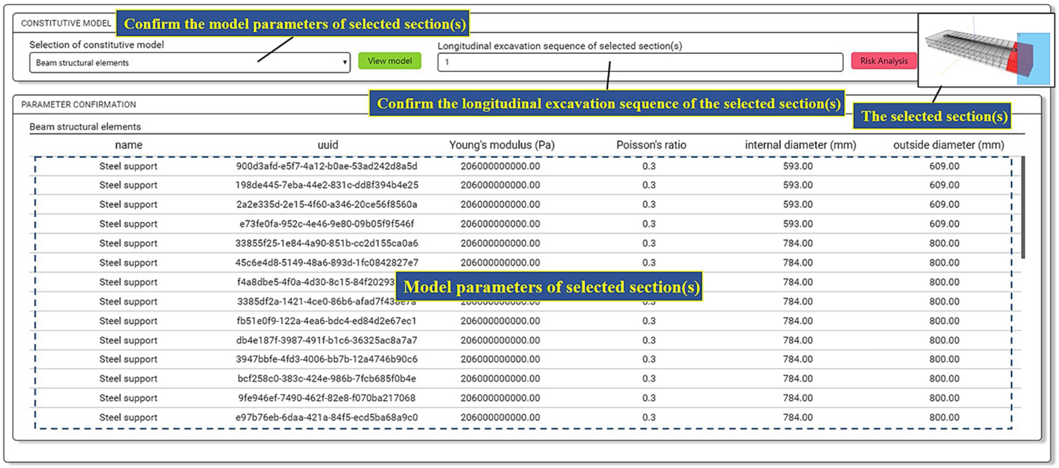

Figure 25. Information on the constitutive models and construction stage to be submitted

a) b)

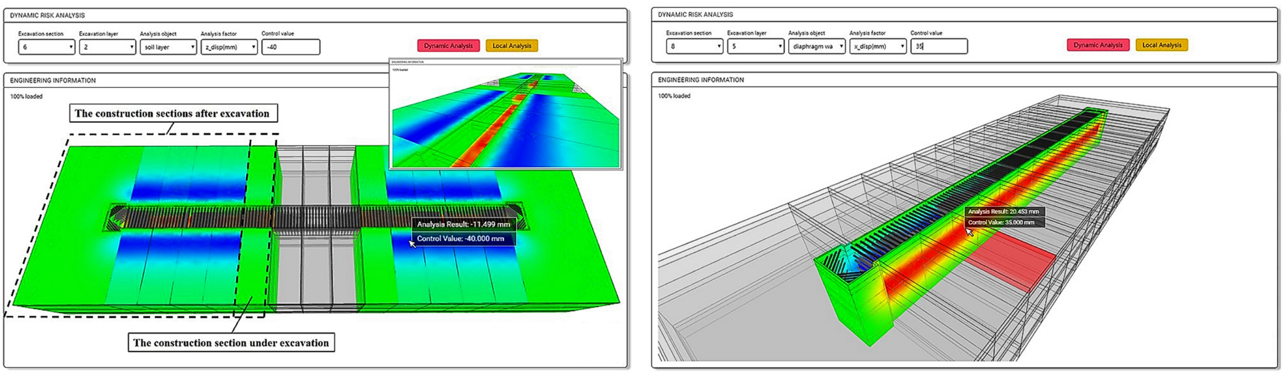

Figure 26. Contour figure in the BIM-FEM/FDM integrated platform: a – ground surface settlement; b – wall deflection

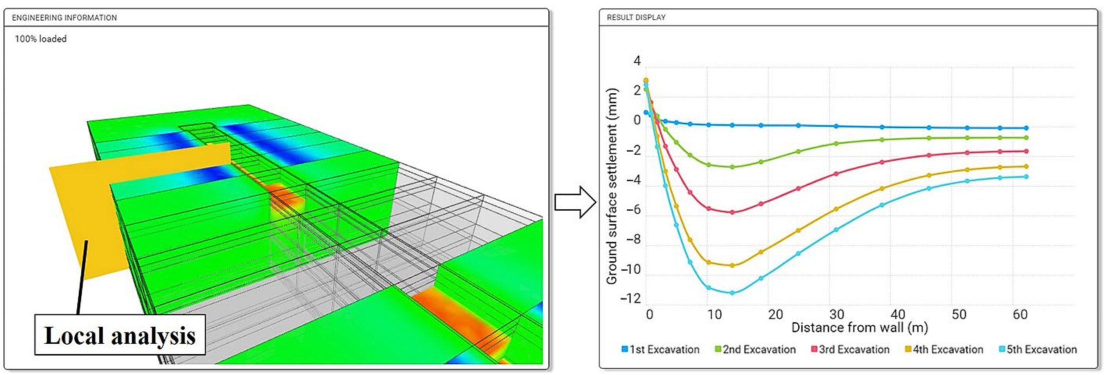

Figure 27. Ground surface settlement curves for various excavation steps

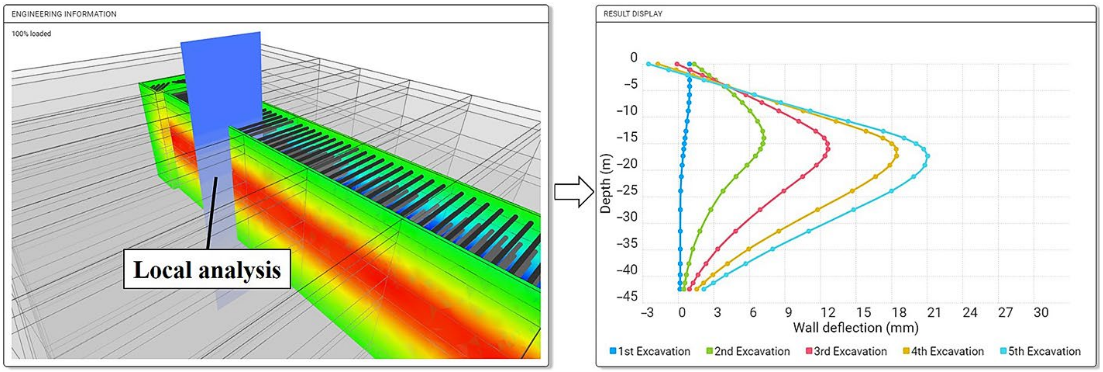

Figure 28. Diaphragm wall deflection curve in local analysis

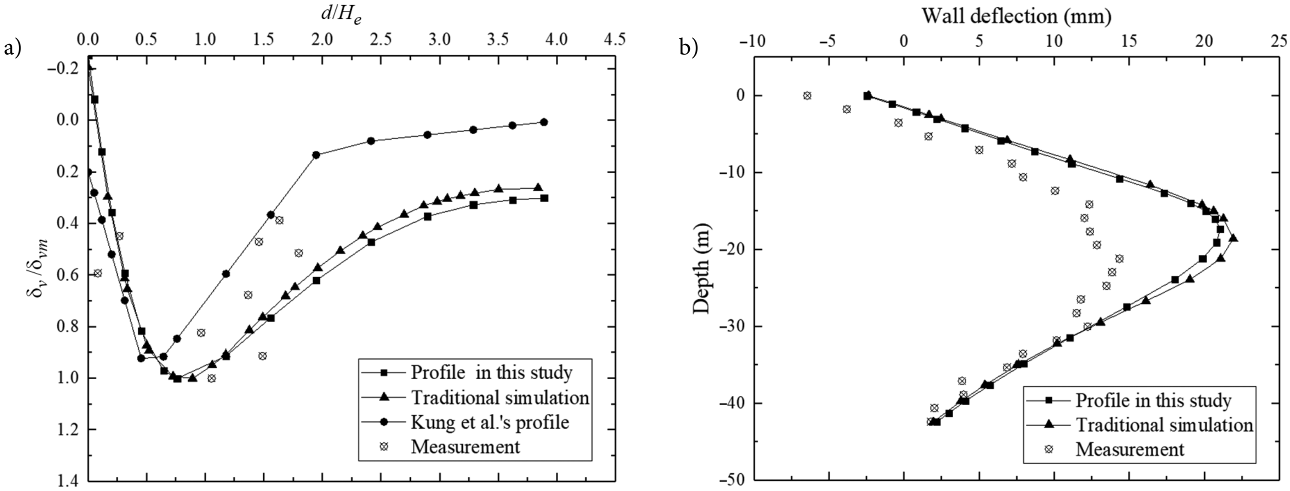

Figure 29. Verification of the simulation results of the BIM-FEM/FDM integrated platform

et al., 2018; Ying et al., 2020) have introduced the selection of the soil constitutive models and corresponding model parameters from the perspective of geotechnical technicians. If necessary, these ways can be used to improve the calculation accuracy in the BIM-FEM/FDM integrated technology proposed in this study.

$$\delta_v = \left(1.6 \times d / H_e + 0.2\right)\delta_{vm} \text{ for } d / H_e \le 0.5; \quad (1a)$$

$$\delta_v = \left(-0.6 \times d / H_e + 1.3\right)\delta_{vm} \text{ for } 0.5 \le d / H_e \le 2.0; \quad (1b)$$

$$\delta_v = \left(-0.05 \times d / H_e + 0.2\right)\delta_{vm} \text{ for } 2.0 \le d / H_e \le 4.0, \quad (1c)$$

where d is the distance from the wall; H_e is the excavation depth; δ_v is the ground surface settlement at the distance d; δ_{vm} is the maximum ground surface settlement.

Conclusions

There are no reports or literature on relevant studies of BIM-FEM/FDM integrated technology for the construction of subway stations implemented by CCM. Related studies have focused on the risk management with BIM technology for deep excavation or BIM-FEM/FDM interoperability approaches for tunnel construction. The construction of subway stations is full of complexity: (1) the synergy and alternation between the support system installation and soil excavation within the superimposed spatial domain, (2) the complicated types of built-up members, and (3) the complex distribution patterns, conditions and nonlinear engineering properties of the soil layers. The present work recognizes the potential of the application of the BIM approach to subway station excavation using the CCM and proposes a parametric modeling method integrated with geometric information, geological-geotechnical information and the construction process.

An FEM/FDM-process oriented data conversion is specifically developed to extract and process the critical information from the parametric model: a CM-based data transmission and storage structure is built to handle the model parameters, a dynamic meshing scheme that considers the construction sequence with advancing front algorithms is developed to promote the automatic simulation process, and an oriented bounding box (OBB) is utilized to determine the boundary conditions of the engineering objects.

In addition, an auto-simulation procedure, including a simulation drive and result processing program, is implemented to realize the automatic simulation process and FEM/FDM-to-BIM interoperability, in which a process of data storage and visualization of the simulation results based on a JSON format data structure is proposed. The proposed BIM-FEM/FDM integrated technology was applied to a case study of a subway station excavation using the CCM. The simulation results of the BIM-FEM/FDM integrated platform have been evaluated using traditional manual simulation.

Generally, it can be recognized that the information transmission and conversion among different BIM software packages are quite flexible. However, FEM/FDM software is not yet completely interoperable with BIM solutions. The most common approach is to import the geometric information from the parametric BIM model into the FEM/FDM software, generate mesh and define the numerical model with some manual operations. To automate this process, the transition from the BIM model-oriented data processing mode to the FEM/FDM process-oriented data processing mode is necessary, and this study has made a preliminary attempt. A limitation of this study is that the uncertainties of the soil properties are not considered in the simulation. Generally, soil is a heterogeneous mixture since it is composed of different components with different characteristics. Consequently, it would be interesting to assess the effects of the uncertainties of the soil properties and it can be further studied.

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Author contributions

Ping Xie, Rongjun Zhang and Junjie Zheng have conceived the study and were responsible for the design and structure of the paper. Ping Xie and Ziqian Li were responsible for BIM-based platform development and data analysis. Ping Xie wrote drafts of the paper.

Disclosure statement

Nothing to declare.

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