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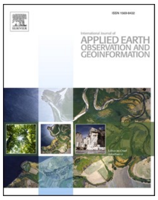

A boundary and voxel-based 3D geological data management system leveraging BIM and GIS

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ABSTRACT

Geological information is a prerequisite of civil engineering infrastructure projects. However, the modeling, representation, update, and exchange of geological information are challenging because they are managed by heterogeneous data models supported by two-dimensional (2D) representation that lacks volumetric information, 3D visualization, and integration. This study presents a novel geological data model using BIM and GIS to facilitate three-dimensional (3D) modeling and management of geological information. The proposed geological data model contains significant geometric, semantic, and spatial information, for which the IFC and CityGML ADE is extended. The BIM and GIS data has been mapped using IFC and CityGML. Moreover, the proposed geological data model uses a boundary and voxel geometric representation for the geological data. Algorithms are developed to create an efficient 3D geological boundary and voxel model based on the developed geological data model. Furthermore, the voxel size, number, and attributes can be updated efficiently, enabling the representation of geological information at different scales. Subsequently, the proposed BIM-GIS framework is demonstrated in a case study using geotechnical investigation data from a city. A questionnaire survey was conducted to verify the practical implications of the proposed method. Consequently, it was found that the proposed method improves geological data management efficiency and the geological information exchange process, which further facilitates the analysis by providing effective 3D visualization, inhomogeneous geological information, and enhancing integration.

1. Introduction

Subsurface geological information is essential during the planning, design, and construction of civil engineering projects, particularly for infrastructures, such as buildings, bridges, roads, railways, tunnels, etc. For example, geological information can help infrastructure planners select a safe building site or feasible route for roads, railways, and tunnels during the planning stage. In the design stage, the structural components of the infrastructures are designed based on the soil conditions (Ninić et al., 2019). The construction sites, specifically the underground construction, are exposed to severe risks and accidents that affect project cost and duration as the geological conditions are uncertain (Ramirez et al., 2022). Understanding the geotechnical information at a city-level in the preliminary stages can play a crucial role in the construction project, primarily because the prediction of geotechnical information is extremely difficult during the construction stage as the site becomes extremely busy place (Khan et al., 2021).

Generally, geotechnical investigations are performed to collect the geological condition data of the ground. A large amount of geological data are generated during the in-situ and laboratory tests. The geological data is shared among stakeholders in multiple formats, such as Excel spreadsheets, Word reports, PDF documents, and other computer-aided design (CAD) formats supported by two-dimensional (2D) representation. A digital platform that can store, manage, analyze and exchange geological data on a city-level in three-dimensional (3D) representation with a unified format can be very efficient for the stakeholders. The updates, retrieval, and exchange of geological information from such a system are challenging and time-consuming. Riding the digital wave, the collected geological information are still managed using traditional methods that are fragmented, hardly linked, and lack visualization and integration.

Building information modeling (BIM) provides a digital representation of a facility integrating geometric and semantic information (Khan et al., 2019; Teo and Cho 2016). The industry foundation classes (IFC) are used to represent the BIM data providing a spatial structure and integrating fragmented information into a unified data format for

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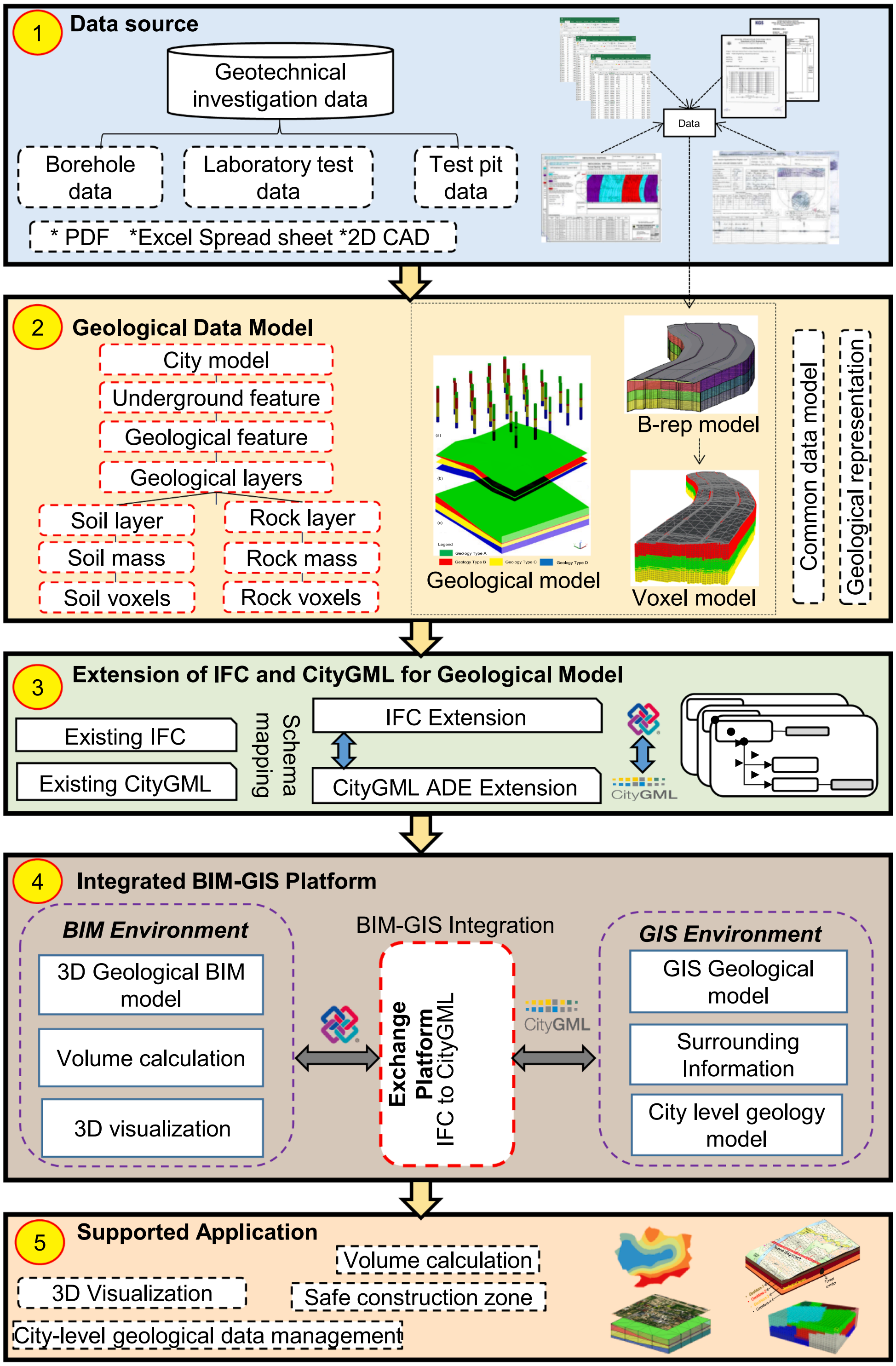


Fig. 1. Proposed framework for developing a BIM-GIS geological data management system.

efficient exchange (Gao and Pishdad-Bozorgi 2019; Khan et al., 2022). Although BIM manages detailed construction project information, city-level information management is difficult. For example, it lacks support for spatial data, geospatial analysis, and surrounding data (Xue et al., 2021). A geographic information system (GIS) represents, stores, analyzes and manages geospatial data at various level including city and rural. The unified data model, city geographic markup language (CityGML), represents, stores, and exchanges the spatial information. Although GIS provides effective data management on a various level supporting geospatial analysis, the information is not comprehensive and detailed (Khan et al., 2021). Therefore, integrating BIM and GIS is considered beneficial for geological data management because the BIM model supports geometric and semantic information at a detailed level. Simultaneously, GIS facilitates city-level geological model visualization and management (Zhu and Wu 2022).

The BIM-GIS integration refers to coupling the BIM and GIS data, which is introduced because of format differences such as IFC, CityGML or shapefile. Recently, many researchers have worked on the BIM-GIS

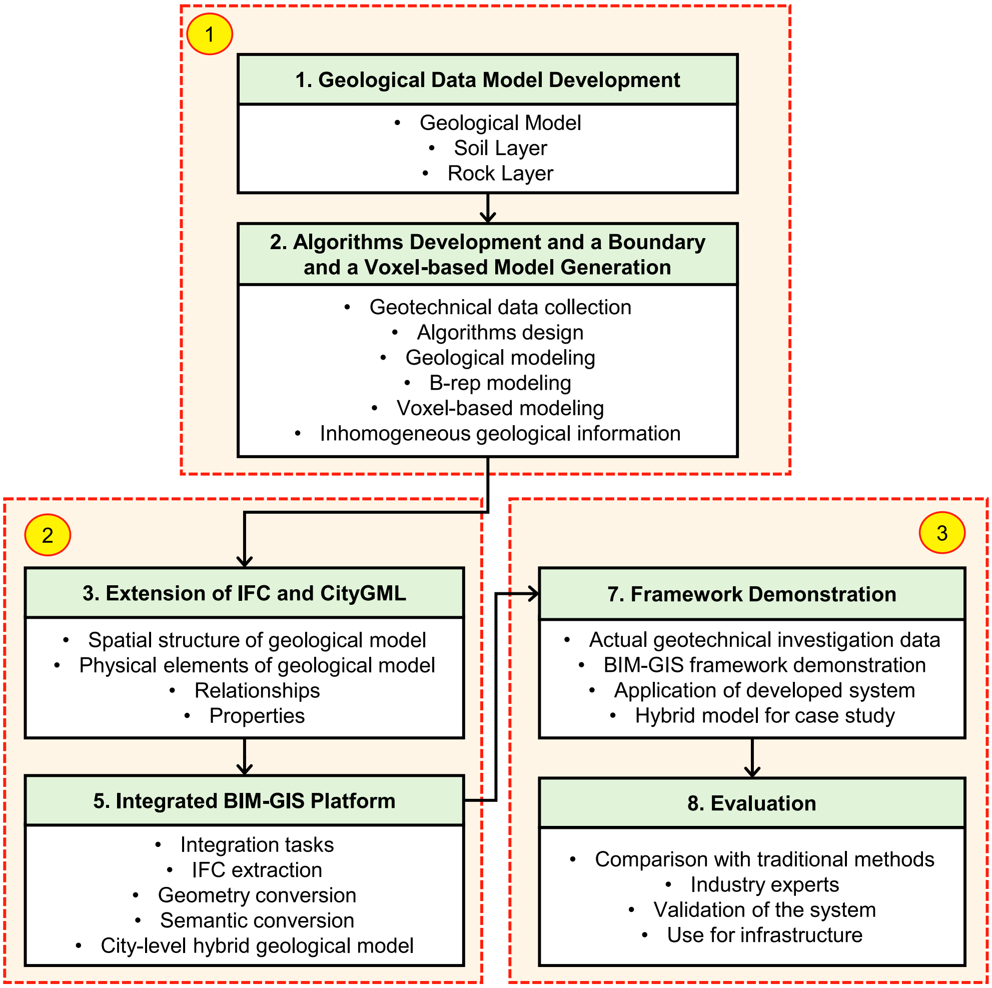


Fig. 2. Proposed research methodology.

integration and applied it in many applications in the construction industry (Ding et al., 2020; Isikdag et al., 2008; Wang et al., 2019; Zhu and Wu 2022). Despite the benefits of the effective BIM-GIS integration, its application for geological data is not easy because of the complex nature of geological information. The BIM-GIS methods adopted for other relevant applications such as buildings (Ding et al., 2020; Kang and Hong 2015; Zhu et al., 2019), bridges (Wan et al., 2019), underground tunnels (Borrmann et al., 2015), utility pipe networks (Cheng and Deng 2015; Sharafat et al., 2021b; Wang et al., 2019), etc., cannot be directly adopted for the geological data because of the differences in the geological as-built data collection, management, modeling, and representation. The geological data are heterogeneous, and there is a three-dimensional (3D) variation. The as-built information for the above surface infrastructure can be easily measured. Various technologies available in the industry can be efficiently used, such as laser scanning and photogrammetry techniques. However, these methods are primarily based on visual contacts and do not apply to the geological data as underground conditions are not visible directly.

Furthermore, geological data management is different since the spatial structure and semantics of the geological elements are unique. For instance, the current data models, IFC and CityGML, lack the geological entities that still need to be defined. Moreover, the modeling and representation for other infrastructures in the BIM-GIS are usually obtained using sweep, constructive solid geometry (CSG), and boundary representation (B-rep), which is more suitable to represent the homogenous elements rather than inhomogeneous bodies like geological models.

There have been efforts to represent the geological data in the GIS and BIM separately. For example, triangular irregular network (TIN) and tetrahedral network (TEN) were used in the GIS to model the geological features (Wenzhong 2000). The TIN is a 2.5D surface-based method lacking the volumetric information, while TEN can represent 3D volumetric information; however, the refinement of the TEN geometries is not possible to support the inhomogeneous geological information at a different scale. Also, some studies have used the B-rep representation to model the geological condition in the BIM environment (Khan et al., 2021; Wu et al., 2021). The B-rep is one of the solid-based representation depicting the homogenous geological volumes. It is composed of several homogenous volumes where each volume represents a geological material such as sand, clay, rock or gravel. However, in practice, the geological volumes are not homogenous, and it often has fluctuations. Even for a single geological material type, other properties can vary, such as moisture contents, etc., and it can include boulders, inclusion or fault materials (Xi et al., 2021). Thus, B-rep cannot represent the microscale inhomogeneous information. Hence, there is a need to develop a model that can represent microscale inhomogeneous information in the geological data.

B-rep and voxel-based representation is considered effective in this case to take care of such challenges. Voxels are the 3D analogy of pixels; each voxel has a volume in space and the division can be performed in a detailed level (Chen et al., 2022). Voxels are 3D cells equally spaced in a 3D environment showing volumetric information obtained by voxelization of the meshes and surfaces (Li et al., 2020). Each voxel can be appended with semantic information. The inhomogeneous regions in the

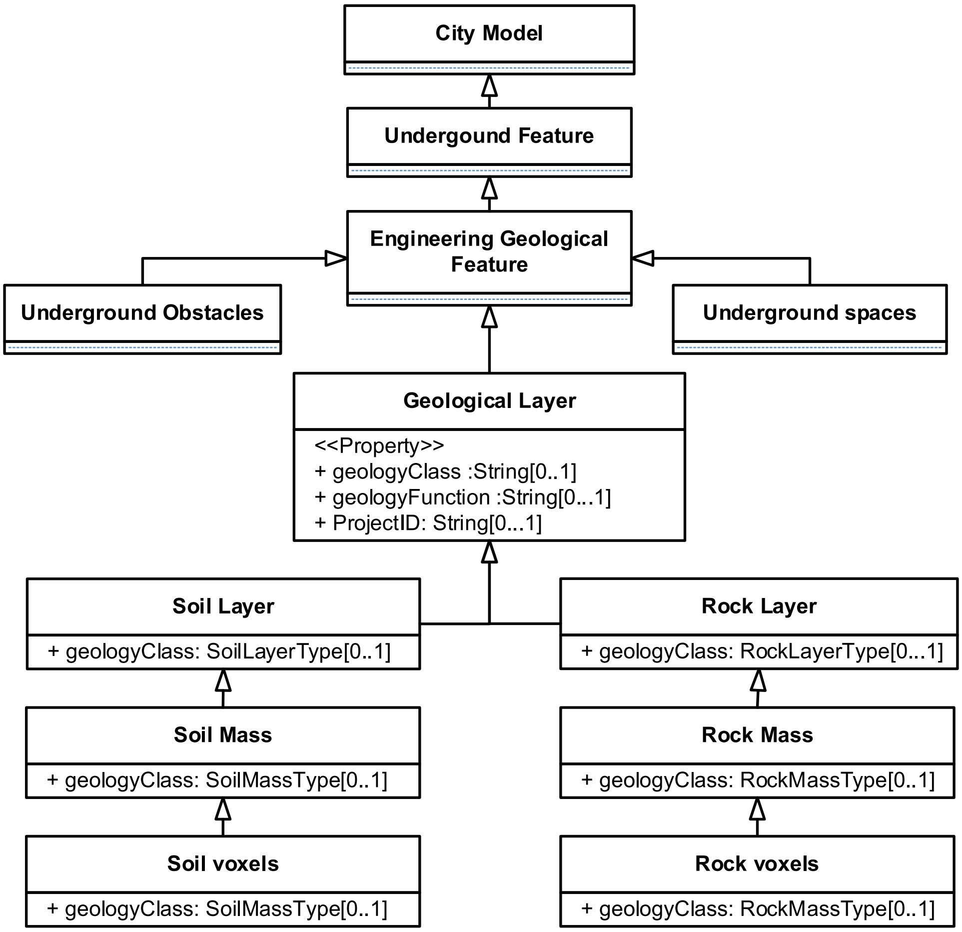


Fig. 3. UML diagram of the proposed geological data model.

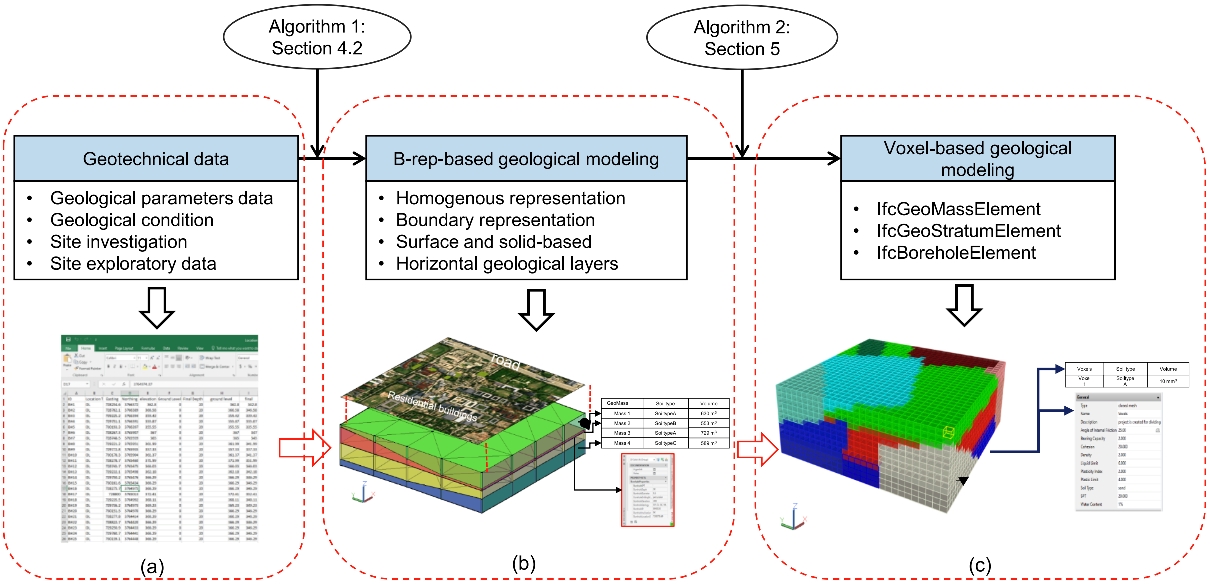


Fig. 4. Process of creating B-rep and voxel-based model, (a). Geotechnical data, (b). Developed B-rep geological model, and (c) voxel-based geological model.

geological model can be efficiently represented with the voxels. Furthermore, the geological information can be queried on a very detailed level. Unfortunately, the BIM and GIS models are not created in voxel-based manners. Therefore, some algorithms need to be developed to convert the homogenous B-rep geological model into a voxel-based to represent the inhomogeneous information. Considering the above challenges in the traditional methods for modeling, representation, exchange, and management of the geological data, a new applicable method must be developed.

This study presents the use of BIM and GIS for the geological data

Table 1
Pseudocode of the developed algorithm for creating a 3D geological model.

```
Algorithm 1
Input: Total number of boreholes (n), number of geology layers/materials/segments
    in each borehole (g), top of each geological layer/segment (t), bottom of each
    geological layer/segment (b),
Output: 3D geological model
1. Load input parameters
2. Draw boreholes in 3D
    i. for borehole $i = 1$ to $n$:
        a. Draw point $Pi$ using easting, northing, and elevation in the x,y-plane
        b. for geology layer/segment $j = 2$ to g(i)
            • Draw vertical points $Pj$
            • Draw a polygon using point Pj as a center (a circle is used in the paper for clear and
              better visualization)
            • Find depth d(j) of each geological layer/segment:
                a. $d(j) = g(j)-g(j-1)$
            • Apply multiple extrusions using top t(j) and depth d(j) information of borehole
              segments
        c. Return borehole segments
            • Append geological information to each borehole segment
            • Assign different colors to each borehole segment using geological properties
    ii. Return boreholes in 3D
3. Generate geological masses
    i. for geological material $M = Mi$ to $Mn$
        a. Identify top points of the geological layer/segment in the study region
            • Interpolate the top points
            • Obtain the top geological layer of M
            • Append geological information
        b. Identify bottom points of the geological layer/segment in the study region
            • Interpolate the bottom points
            • Obtain the bottom geological layer of M
            • Append geological information
        c. Extract geological mass /solid by comparing top and bottom geological layers
            • Append geological information
        d. Return geological information
```

management. A geological data model extending IFC and CityGML for the geological data is proposed. Moreover, a boundary and voxel-based approach are beneficial in representing the homogenous and inhomogeneous geological features. The contributions of this study to enhance the existing knowledge area are as follows.

1. A 3D geological data model is introduced for large areas, representing all necessary information. The proposed geological data model is used as a base model to extend the IFC and City GML classes and support integration.
2. A boundary and voxel-based geometric representation are proposed. Two algorithms have been developed. The first algorithm is developed to generate a B-rep-based 3D geological solid model efficiently. The second algorithm converts the B-rep model into the voxel-based model. The algorithms are efficient enough to incorporate all the necessary geological information and represent the inhomogeneous regions in the geological space.
3. The IFC and CityGML data model for geological entities such as IFC and CityGML classes, properties, and relationships are defined to introduce an open data geological model for efficient information exchange and integration.
4. Integrating BIM and GIS using extended IFC and CityGML class mapping enhances the geological data exchange and sharing process at different stages of an infrastructure project.
5. The BIM-GIS geological model that stores, manages, and updates geological information, including geometric, semantic, and spatial information at the planning, design, and construction stages, is developed. The benefit of this model is that the inhomogeneous geological information can be stored and managed in 3D volumetric representation at a different scale, facilitating 3D detailed visualization and integration.

2. Literature review

2.1. Geological modeling

Geotechnical investigations are generally performed to investigate the geological condition (Asadzadeh and de Souza Filho 2016). It provides detailed information about a site's geological condition, such as underground space's mechanical and physical characteristics. A site's geological condition is primarily inhomogeneous and its properties vary in three-dimension (3D). Traditionally, the geological condition data are stored, presented, and analyzed in a multiple-format system. The traditional methods manage the geological data isolated, lacking integration, exchange, and coordination among team members. Although, there are software products that provides basic 2D or 3D visualization; however, it still uses multiple format system (Breunig et al., 2016; Gabriel et al., 2015). This data needs to be modeled and managed in an integrated 3D environment representing the inhomogeneous geological information and integrating the semantic and spatial geological data.

For modeling, the surface and solid-based representation can be used. The surface-based representation normally used for the geological models includes triangulated irregular networks (TIN) that support geospatial analysis but don't include volumetric information (Wenzhong, 2000). There are three existing models for solid-based representation: construction models, boundary models, and decomposition models (Shah and Mäntylä, 1995). The construction models such as constructive solid geometry (CSG) are a combination of primitives that don't focus on topology, which is why they are unsuitable for geological modeling. The boundary model (B-rep) represents the solid bodies by volumes obtained by the surrounding faces. The B-rep represents the volumetric information and supports the integration of semantic information; however, the B-rep models are integrated, and the division into smaller parts is difficult to represent the inhomogeneous information in the geological model. Thus, another representation that could address these issues is needed.

The decomposition model represents the solid body by decomposing it into several cells. One decomposition model is the tetrahedron network (TEN), which is a 3D extension of the TIN. It is formed by linking the triangles of the TIN that represent a geological volume or mass (Lee et al., 2020). There exist some software packages such as Paradigm Skua-Gocad or Schlumberger Petrel that uses TEN for the volume-based geological; however, this method offer some limitation. The TEN-based geometries represent the geological model at a coarse level, and the refinement of the TENs is not possible to support inhomogeneous geological information at different scales or lower levels (Hegemann et al., 2013; Koch et al., 2017; Wenzhong, 2000). Voxel is another decomposition model, a 3D cells/cube representing the volumetric information. Depending on the geological condition, the geological condition can be represented with the different voxel sizes. The small voxels can represent the inhomogeneous regions, while large voxels can be used for homogenous regions. Each voxel can be integrated with semantic and spatial geological information. The flexible refinement into the different sizes, representation of inhomogeneous information at a different scale, and integration of semantic information are the advantages of the voxel-based modeling for geological data, which has been rarely explored in previous studies.

Voxelization is the process of the converting the geometric meshes into the voxels. Considering the voxel size, two kind of voxelization strategies can be adopted; self-adapting and identical-size voxelization (Shoaib Khan et al., 2021; Wang et al., 2020). Octree and LEGO-based models are two format of the self-adapting voxelization. In this strategy, voxels have various sizes in a geological mesh. This strategy is difficult to handle when exchanging information from BIM to GIS using IFC. On the other hand, the identical-sized voxelization creates identical size voxels for a specific mesh. The size of voxel can be change for each mesh depending on the geological condition. Identical-size voxelization strategy is adopted for efficient information exchange.

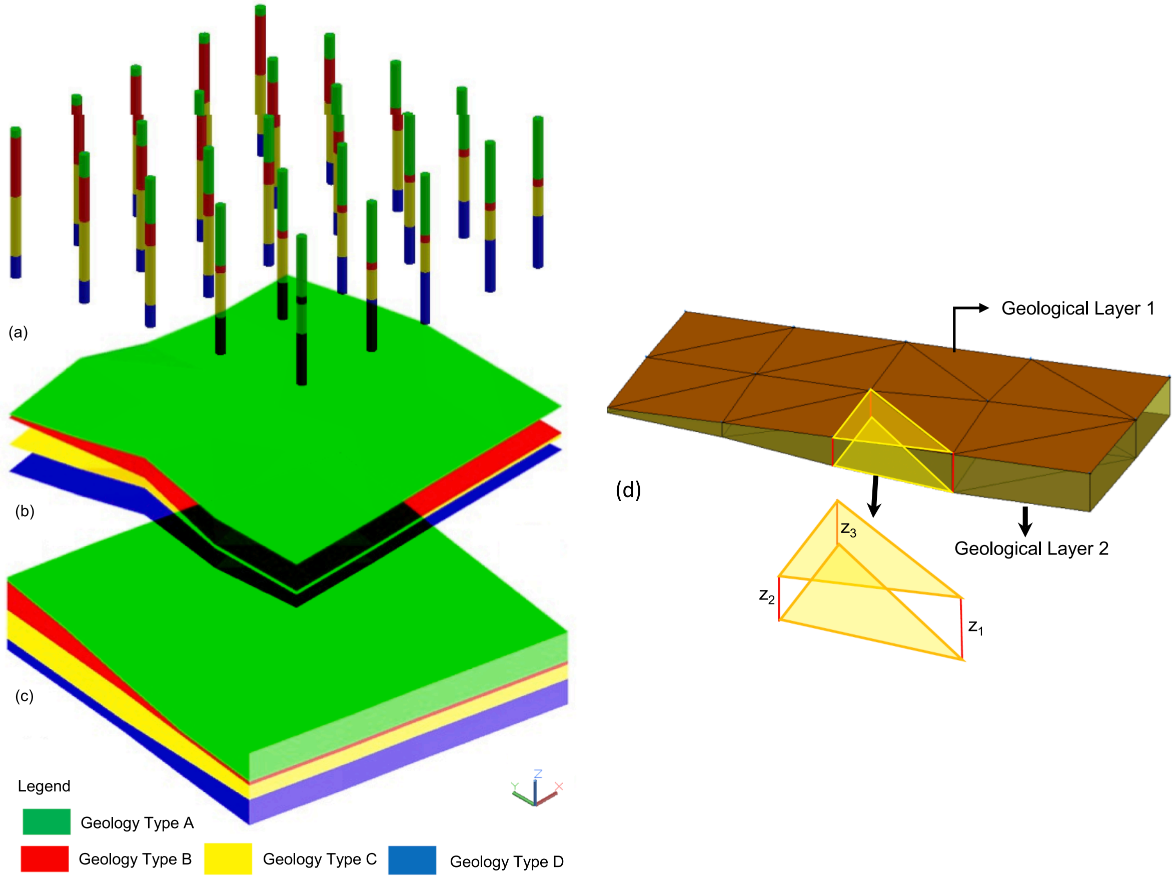


Fig. 5. 3D geological modeling of geological elements generated using the developed algorithm, (a) borehole visualization; (b) geological stratum; and (c) geological masses (B-rep models), (d) the process of constructing solid from the surfaces.

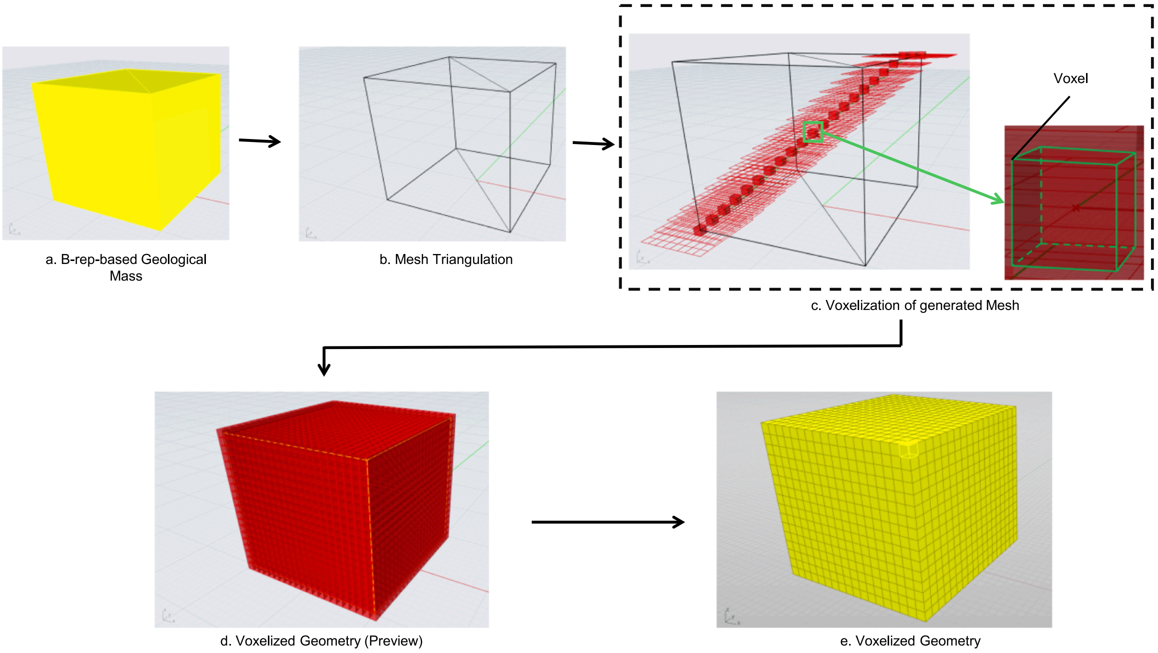


Fig. 6. Voxelization of a B-rep geological model.

2.2. BIM-GIS application for geological data

GIS stores, manages, and analyzes the geographical data that has been widely used for planning construction projects. The advancement in the 3D GIS to represent, store, and exchange city information has been increasing continuously. Several studies exist that uses TIN and TEN

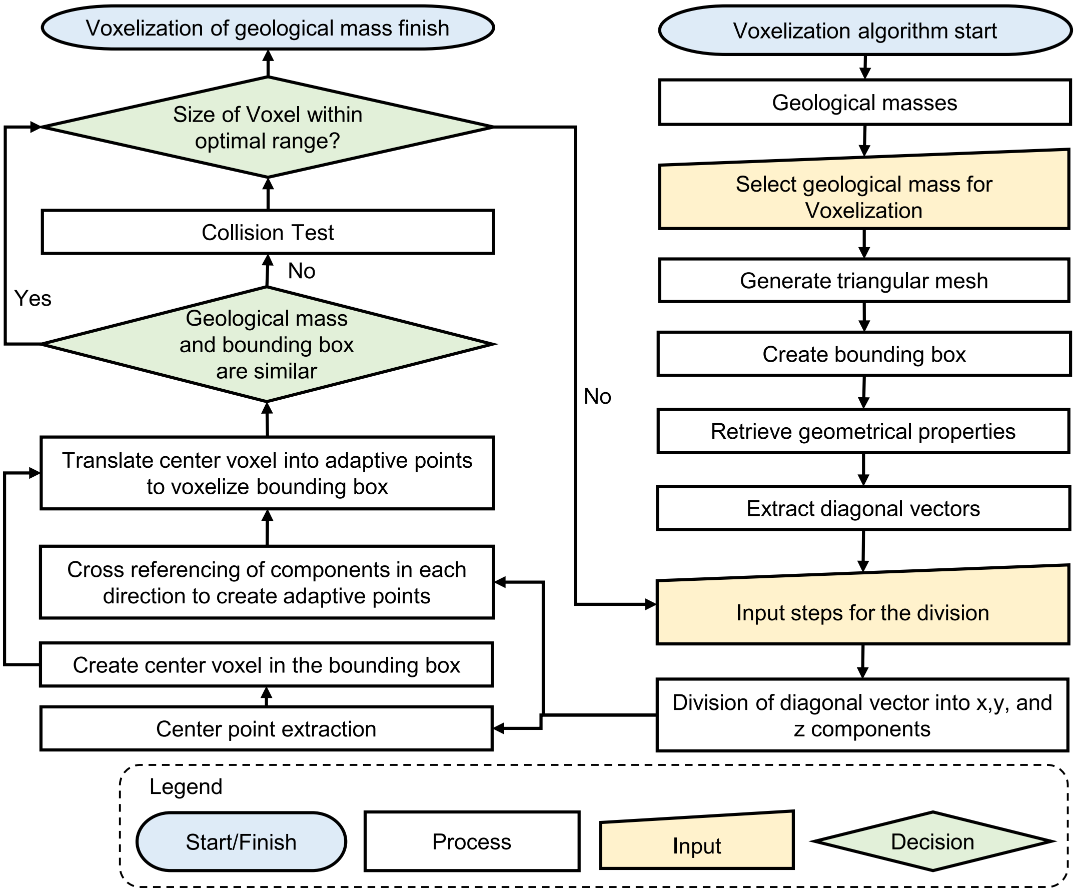


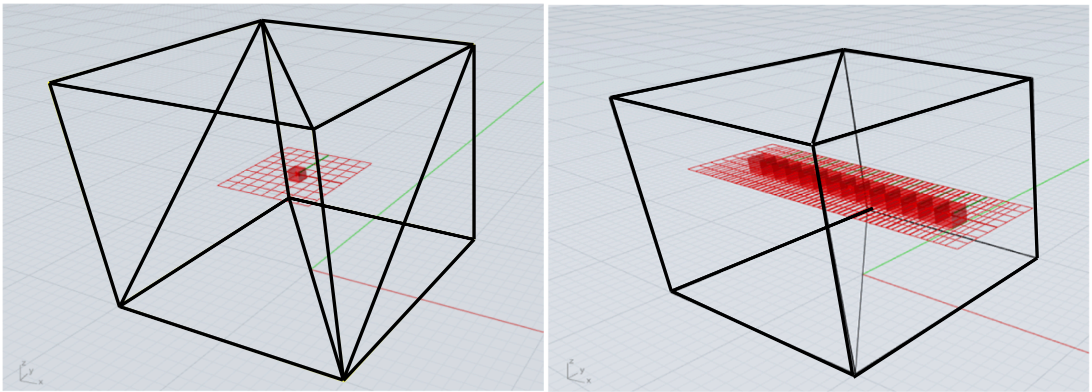
Fig. 7. Voxelization algorithm.

representation to model geological features [28]. However, these methods have limitations such as lacking 3D visualization, volumetric information, and decomposition into smaller parts to include inhomogeneous information. Surface-based models such as B-rep representation is commonly adopted for 3D modeling and visualization in the GIS environment. Although GIS supports 3D models nowadays, the semantic data in GIS is not comprehensive. On the other hand, BIM facilitates the construction projects with the digital representation integrating geometric and semantic information into a single database.

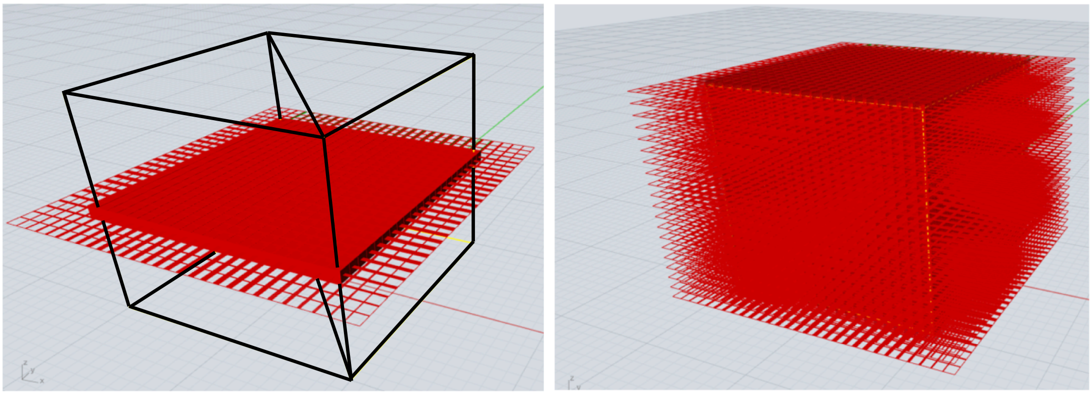
Due to the multi-source and heterogeneous geological exploration data, BIM models in IFC for geological model are rarely built. There have been some efforts for the BIM application to model geological data with semantic information. For example, the geological data has been modeled in recent studies for tunnels and underground caverns (Huang et al., 2022; Sharafat et al., 2021a). However, these studies have used B-rep, sweep, Constructive Solid Geometry (CSG), etc, for modeling in the BIM environment, which are mainly suitable for the regular and homogenous objects modeling such as structural and architectural elements. However, geological elements have different characteristics and their properties changes in three-dimension, which is difficult to be represented in the object-oriented BIM model. Furthermore, these studies are applicable only for small regions, as it is challenging to facilitate city-level geological modeling in the BIM environment. The BIM and GIS integration is considered effective because the integrated BIM-GIS can facilitate; (i) city-level geological model and (ii) geometric, semantic, and spatial data integration.

The BIM-GIS has been integrated for several applications in the construction industry to utilize their combined features, such as infrastructure planning (Zhao et al., 2019a,b), tunnels and bridge facility management (Dang and Shim, 2020), underground utility management (Irizarry et al., 2013), and geotechnical property modeling (Khan et al., 2021). BIM-GIS integration can be achieved at the application and data levels. At the application level, integration is achieved for a specific use, and BIM or GIS data format does not change (Liu et al., 2017; Wyszomirski and Gotlib 2020). Recently, the GIS point borehole data was integrated with the BIM for the visualization of 3D boreholes and volume calculation (Khan et al., 2021). However, this integration strategy mainly focuses on geometry, while semantics is not necessary. The data-level integration is achieved by fusing the data models of both platforms because BIM and GIS use different data formats. For example, BIM uses a semantic data model such as IFC, whereas GIS uses either a non-semantic data format (i.e., shapefile) or semantic data model (i.e., CityGML) (Zhu and Wu, 2022). However, the non-semantic data format shapefile is unsuitable for geological modeling because it uses multi-patches for solid representation, and the semantic data is stored separately in the relational databases. Also, the spatial relationship is not efficiently represented in the shapefile, which means that the relationship between model objects are ineffective that play a key role to organize and manage a project efficiently (Zhu and Wu, 2022).

Integrating BIM and GIS using IFC and CityGML requires geometric conversion and semantic mapping. The geometry conversion is needed because the modeling paradigm in BIM and GIS is different. BIM mainly uses B-rep, Constructive Solid Geometry (CSG), swept, and surface representation for modeling, while GIS uses B-rep and surface representation (Zhu et al., 2020). The CSG is a construction solid model, and sweep creates a solid model using a profile, while surface-based models lack volumetric information. Hence, they are not suitable for geological models. Furthermore, CSG and swept geometries conversion from IFC into the B-rep geometries in CityGML is time-consuming and loses necessary information during transformation (Deng et al., 2016; Zhu et al., 2020). The B-rep model can efficiently integrate BIM and GIS without geometry transformation. Some studies exist that convert BIM



a. Center Voxel b. Voxels in U Direction



c. Voxels in U and V-Direction d. Voxels in U,V and W-Direction

Fig. 8. Identification of voxel values inside of a bounding surrounding a mesh, (a) center voxel generation, (b) voxels translation in U-direction, (c) voxels translation in U-V plane, and (d) voxelization of the bounding box.

data into the GIS considering B-rep representation (Deng et al., 2016; Zhu et al., 2019). However, these studies convert the BIM semantic data (IFC) into the GIS non-semantic data (shapefile). Hence, the B-rep (IFC) to B-rep (CityGML) must be explored that can represent a 3D geological solid model, volumetric information, and support analysis.

The semantic mapping is required to ensure the connections between IFC and CityGML classes. The semantics refers to the attributes and information attached to each element and the relationship between these elements. The existing IFC and CityGML semantics defined by BuildingSMART and Open Geospatial Consortium (OGC) can be used to establish a link between the two classes (BuildingSMART, 2018; Kolbe et al., 2021). The extended classes can be used if elements are not defined in the IFC and CityGML schemas (Zhu and Wu 2022). The IFC and CityGML semantics for the geological entities still needs to be defined. Some researchers have used these strategies in recent years for utility management and tunnel infrastructure (Deng et al., 2016; Wang et al., 2019). However, each infrastructure's semantics are different and must be defined separately (Motamedi et al., 2016).

Meanwhile, in the IFC extension, new entities are proposed following an object-oriented approach, and the entities' properties and relationships are defined (Motamedi et al., 2016; Sharafat et al., 2021a; Zhou et al., 2018). Similarly, the application domain extension (ADE) concept is used to extend and define objects' classes, properties, and relationships in the CityGML (Biljecki et al., 2018). In this study, the IFC and CityGML ADE, specifically to geological data, are extended and mapped to achieve BIM-GIS integration. The BIM-GIS integration proposed in this study is different than previous studies because this study considers (1) B-rep (IFC) to B-rep (CityGML), (3) Semantic definition for the geological entities, (2) incorporation of inhomogeneous information, and (3) application to geological data.

3. Proposed framework and geological data model

3.1. Proposed framework

This study proposes a framework for the geological model using BIM and GIS. The proposed BIM-GIS framework is shown in Fig. 1, which primarily consists of (i) the collection of the geotechnical investigation data; (ii) geological data model development; (iii) development of boundary and voxel-based geological model; (iv) extension of the IFC and CityGML ADE for the geological model according to the developed data model; (v) BIM and GIS data mapping using the proposed IFC geological classes into the CityGML classes; and (vi) application supported by the developed integrated model.

The stepwise method adopted for this study is depicted in Fig. 2. The manuscript has been divided into three sections; geological modeling, IFC and CityGML extension, and demonstration and evaluation. First, a geological data model is proposed to define all the geometric, semantic, and spatial information necessary for geological data management. Algorithms were developed to generate boundary and voxel-based geological models. The IFC and CityGML classes were extended based on the developed data model in the subsequent section. Furthermore, the extended IFC and CityGML classes were mapped from BIM into the GIS. The proposed method was demonstrated using city geotechnical investigation data. Ultimately, the developed framework was verified by two methods: (1) comparison with the traditional methods and (2) collecting feedback from potential users in the civil engineering industry.

3.2. Geological data model development

A city model consists of many surfaces and subsurface objects. An

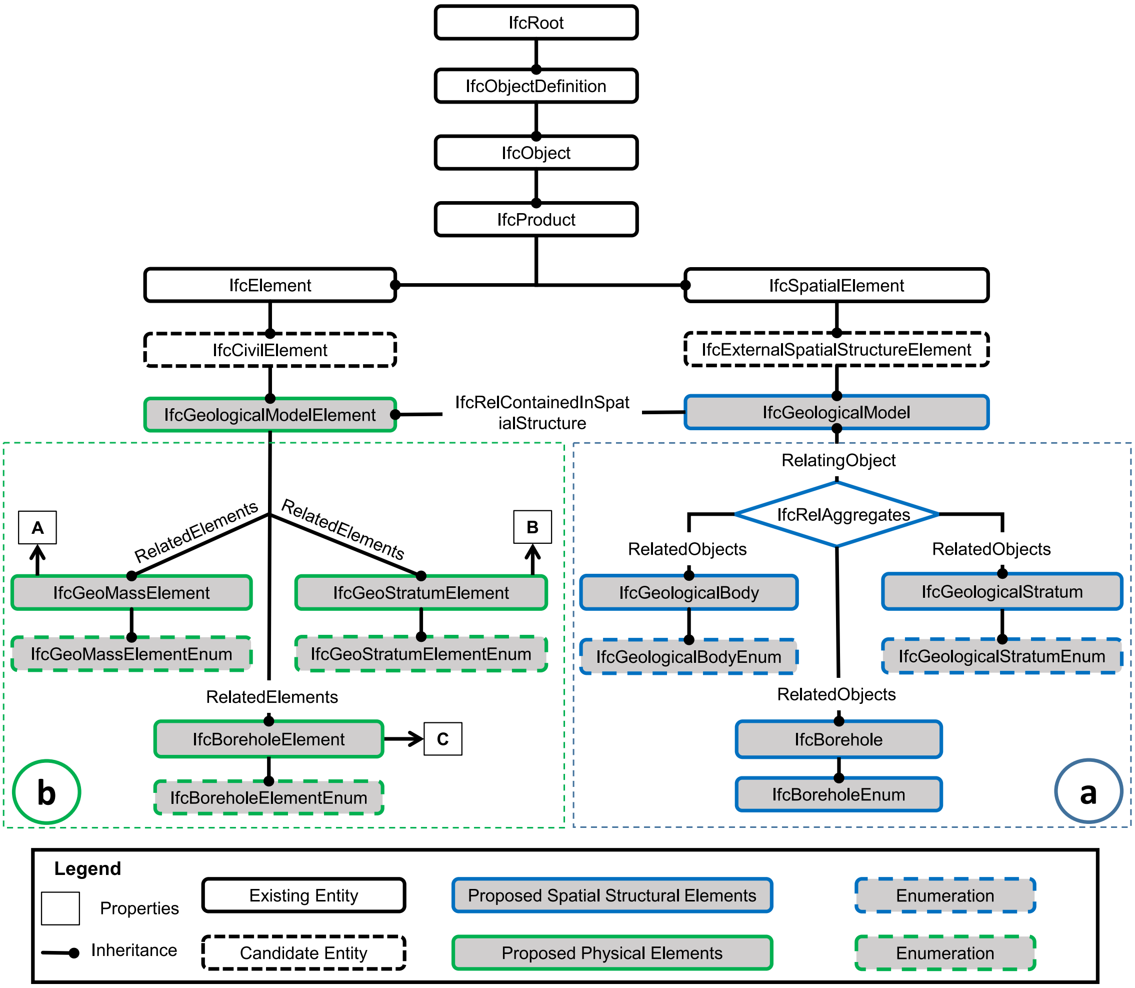


Fig. 9. EXPRESS-G diagram representing the extension of the IFC entities for the geological information modeling.

underground space consists of several objects, such as water, utility lines, spaces, and geology. For instance, a 3D geological model consists of numerous geological entities, such as geological strata, blocks, and cavities. The scope of this study was limited to considering the engineering geological elements of underground spaces. The data model proposed in this study is shown in Fig. 3. The UML diagram shows the data model that acts as a base for the extension of the IFC and CityGML to represent geological entities.

An abstract class geological layer was used to represent geological features in the underground space. It defines the geological features that are available as continuous layers in an underground space. The geological layer in subsurface space has a comparatively homogenous composition with well-defined top and bottom boundaries. Depending on the layer material type in the underground space, the geological layer is further categorized into soil and rock. The volume of the soil or rock material in a specific region is defined using the soil mass or rock mass. The inhomogeneous information, such as the change in the geological properties or inclusions in the underground space, is represented with voxels. Thus, the proposed geological data model supports homogenous and inhomogeneous geological information.

4. B-rep-based geological model

To realize the representation of the homogenous and inhomogeneous geological information, a boundary and voxel-based geological data model using BIM and GIS is proposed.

The B-rep model represents the geological information in horizontal layers having number of homogenous volumetric regions. Each region in the B-rep model represents unique characteristics of the ground. For example, homogenous material of soil or rock are represented with the B-rep in 3D environment. Each region has set of surfaces that characterize the layer boundary. Semantic information such as material, type, strength, classification, etc can be attached to each homogenous layer.

On the other hand, the voxel-based model consists of 3D cells representing the inhomogeneous geological information. Each voxel are associated with the geological information. The inhomogeneous regions are efficiently represented with the voxel. Furthermore, the variation in the geological properties in a specific region can be represented with the voxels of various sizes. Voxel-based model are structured that has advantage in term of storage requirement and refinement to represent the inhomogeneous regions. For example, the voxel size can be selected based on the inhomogeneity on the geological space enabling the geological data representation at different scales.

The process of boundary and voxel-based model generation is illustrated in Fig. 4. Firstly, geological data is collected that shows the characteristics of the ground. Secondly, an algorithm is used to develop a B-rep geological model utilizing the geological data. Finally, the B-rep model is converted into voxel model. The detail about each step are given in the below sections.

4.1. Geotechnical data collection

The first crucial step is to obtain geological information data to develop a boundary and a voxel-based geological 3D model according to

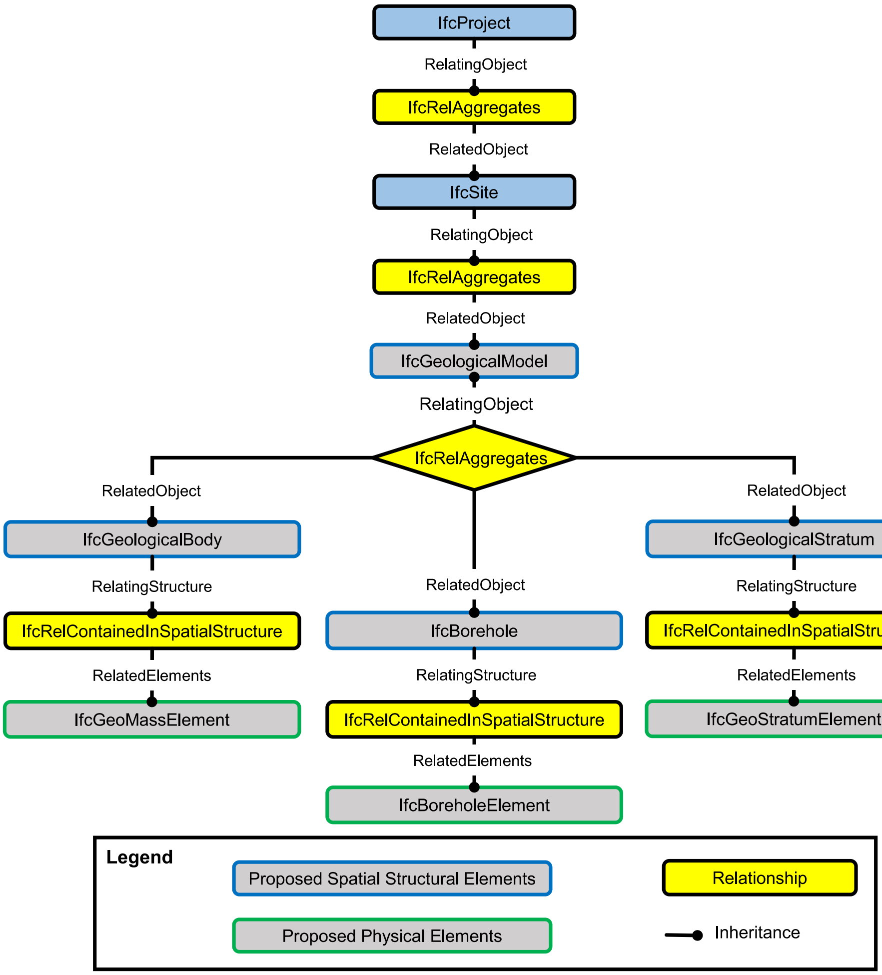


Fig. 10. The hierarchical relationship between the spatial structure elements and the relationship between spatial and physical elements.

the proposed data model. For example, geological data and other parameters describing the study area's geological conditions. This information can be collected from geotechnical investigation reports and exploratory data. These sources include detailed information regarding the project, borehole, field test, and laboratory test that describe the geological condition data, such as the distribution of the geology type information, water table, and other physical and mechanical properties of the soil or rock.

4.2. 3D geological modeling via algorithm approach

Considering the characteristics of the proposed data model, 3D geological modeling can be obtained as (i) 3D borehole modeling, (ii) geological stratum or layer modeling, and (iii) geological body. Accordingly, an algorithm was developed to automate the 3D geological modeling process. The algorithm retrieves geological data from a database to develop a 3D B-rep-based geological model. The pseudocode for the automated geological model generation according to the developed geological data model is presented in Table 1.

First, region and borehole data obtained during the site investigation were selected. The boreholes were modeled in 3D using the developed algorithm. Fig. 5a shows the borehole model visualized in 3D using point data from the site investigation. For example, a single borehole comprises multiple segments. Each segment representing different geological types has a start and end depth. Each segment is characterized by different colors, making it easier to identify the geological type and depth.

A borehole represents information on a single point, and the borehole data can be converted into geological layers to represent the geological variation in the geological space. Spatial interpolation techniques convert borehole point data into geological layers [17]. In this process, it is crucial to interpolate borehole segments of the same soil type because a geological layer with the same geology can be obtained. For example, Fig. 5a shows that a single borehole represents different geological layers characterized by different colors. Interpolation was applied using points of the same soil type. Inverse Distance Weighing (IDW), Triangular Irregular Network (TIN), and Kriging interpolation techniques are common for the geological model that can be used (Kim et al., 2020). A surface-based representation was used to model the geological layers. Fig. 5b shows the geological layers obtained after interpolating the borehole segment data.

The geological layers were obtained for the top and bottom layers each representing unique geological features. Geological bodies were constructed from the same soil-type surfaces (Fig. 5c). It was obtained by joining the vertices of the top and bottom surfaces. Fig. 5d depicts the process of constructing solid from the surfaces. The top and bottom surfaces representing the same geological features are overlaid on each other having vertical projection onto a horizontal plane, thereby generating a set of composite triangles (Lee et al., 2020). Subsequently, truncated triangular prisms are created by projecting each composite triangle onto each of the two surfaces. The triangular prisms representing the geological masses have volumetric geological information and their volume can be obtained. Different geological masses were obtained using surfaces of the same soil type at different depths, which were differentiated by color. Solid-based B-rep representations were used for geological body modeling. Finally, a 3D geological model was

Table 2
IFC Property Definition of the proposed geological entities.

Physical Elements	Property	Property Type	Property Data Type	
IfcGeoStratumElement	Common	StratumID	IfcPropertySingleValue	IfcLabel
		StratumGeologyType	IfcPropertySingleValue	IfcLabel
		StratumTopDepth	IfcPropertySingleValue	IfcLabel
		StratumBottomDepth	IfcPropertySingleValue	IfcLabel
	Physical Properties	StratumLiquidLimit	IfcPropertySingleValue	IfcNumericMeasure
		StratumPlasticLimit	IfcPropertySingleValue	IfcNumericMeasure
		StratumPlasticityIndex	IfcPropertySingleValue	IfcNumericMeasure
		StratumMoisturecontent	IfcPropertySingleValue	IfcRatioMeasure
		StratumUnitWeight	IfcPropertySingleValue	IfcNumericMeasure
		StratumPermeability	IfcPropertySingleValue	IfcNumericMeasure
		StratumSpecificGravity	IfcPropertySingleValue	IfcRatioMeasure
		StratumBulkDensity	IfcPropertySingleValue	IfcRatioMeasure
	Mechanical Properties	StratumBearingCapacity	IfcPropertySingleValue	IfcNumericMeasure
		StratumModulusofElasticity	IfcPropertySingleValue	IfcNumericMeasure
		StratumPoissonRatio	IfcPropertySingleValue	IfcRatioMeasure
		StratumAngleOfInternaFriction	IfcPropertySingleValue	IfcNumericMeasure
		StratumCohesion	IfcPropertySingleValue	IfcNumericMeasure
		StratumShearStrength	IfcPropertySingleValue	IfcNumericMeasure
		StratumShearModulus	IfcPropertySingleValue	IfcNumericMeasure
		StratumUCS	IfcPropertySingleValue	IfcNumericMeasure
		StratumTensileStrength	IfcPropertySingleValue	IfcNumericMeasure
IfcBoreholeElement		ProjectID	IfcPropertySingleValue	IfcLabel
		Client	IfcPropertySingleValue	IfcLabel
		Company Name	IfcPropertySingleValue	IfcLabel
		BoreholeLoggedBy	IfcPropertySingleValue	IfcLabel
		Borehole date	IfcPropertySingleValue	IfcLabel
		Seismic Zone	IfcPropertySingleValue	IfcLabel
		BoreholeID	IfcPropertySingleValue	IfcLabel
		BoreholeDiameter	IfcPropertySingleValue	IfcLabel
		BoreholeLocationX	IfcPropertySingleValue	IfcLabel
		BoreholeLocationY	IfcPropertySingleValue	IfcLabel
		BoreholeTopDepth	IfcPropertySingleValue	IfcLabel
		BoreholeBottomDepth	IfcPropertySingleValue	IfcLabel
		BoreholeWaterLevel	IfcPropertySingleValue	IfcLabel
		BoreholeDrillingMethod	IfcPropertySingleValue	IfcLabel
		BoreholeInclination	IfcPropertySingleValue	IfcLabel
		BoreholeGeologyType	IfcPropertySingleValue	IfcLabel
		BoreholeSPTValue	IfcPropertySingleValue	IfcNumericMeasure
		BoreholeCPTValue	IfcPropertySingleValue	IfcNumericMeasure
		TotalCoreRecovery	IfcPropertySingleValue	IfcNumericMeasure
		RockQualityDesignation	IfcPropertySingleValue	IfcNumericMeasure
IfcGeoMassElement		GeoMassID	IfcPropertySingleValue	IfcLabel
		GeoMassType	IfcPropertySingleValue	IfcLabel
		GeoMassGeologyType	IfcPropertySingleValue	IfcLabel
		GeoMassDepth	IfcPropertySingleValue	IfcLabel
		GeoMassVolume	IfcPropertySingleValue	IfcLabel
		GeoMassStrength	IfcPropertySingleValue	IfcNumericMeasure

constructed, and semantic information was integrated with the geological model. Integrating semantic information with the geological model allows practitioners to perform further analysis.

5. Voxel-based geological modeling

Underground space consists of several types of geological materials that are available in layers. The properties of the geological materials varies in each direction. The inhomogeneous geological materials are represented with the voxels. The voxel size is the main trigger in this proposal to represent the inhomogeneous geological material at different scale. The size of voxel is selected based on the geological condition data. Smaller size is selected for inhomogeneous regions, while bigger voxels are used in the homogenous regions. The developed algorithm automatically convert the generated geological model into voxels with predefined voxel size.

The process of creating a voxel-based model from the B-rep geological model comprises three major steps; (i) generating a 3D solid B-rep-based geological model, (ii) mesh creation, and (iii) voxels creation on the meshes. The voxelization process is presented in Fig. 6. The algorithm developed for generating a voxel-based model is shown in Fig. 7.

5.1. Solid extraction from B-rep model

Firstly, a 3D geological model is generated using B-rep representation, achieved in the above Section 4.2. The B-rep model represents the homogenous geological volume bounding an underground space by surfaces. The first step is to extract solid from the surfaces of the same geological type.

5.2. Triangular mesh generation

In the second step, the solid-based B-rep model is converted into a triangular mesh that consists of several triangular facets. The triangular meshes representing the complex geological surfaces are used to voxelize the geological mass.

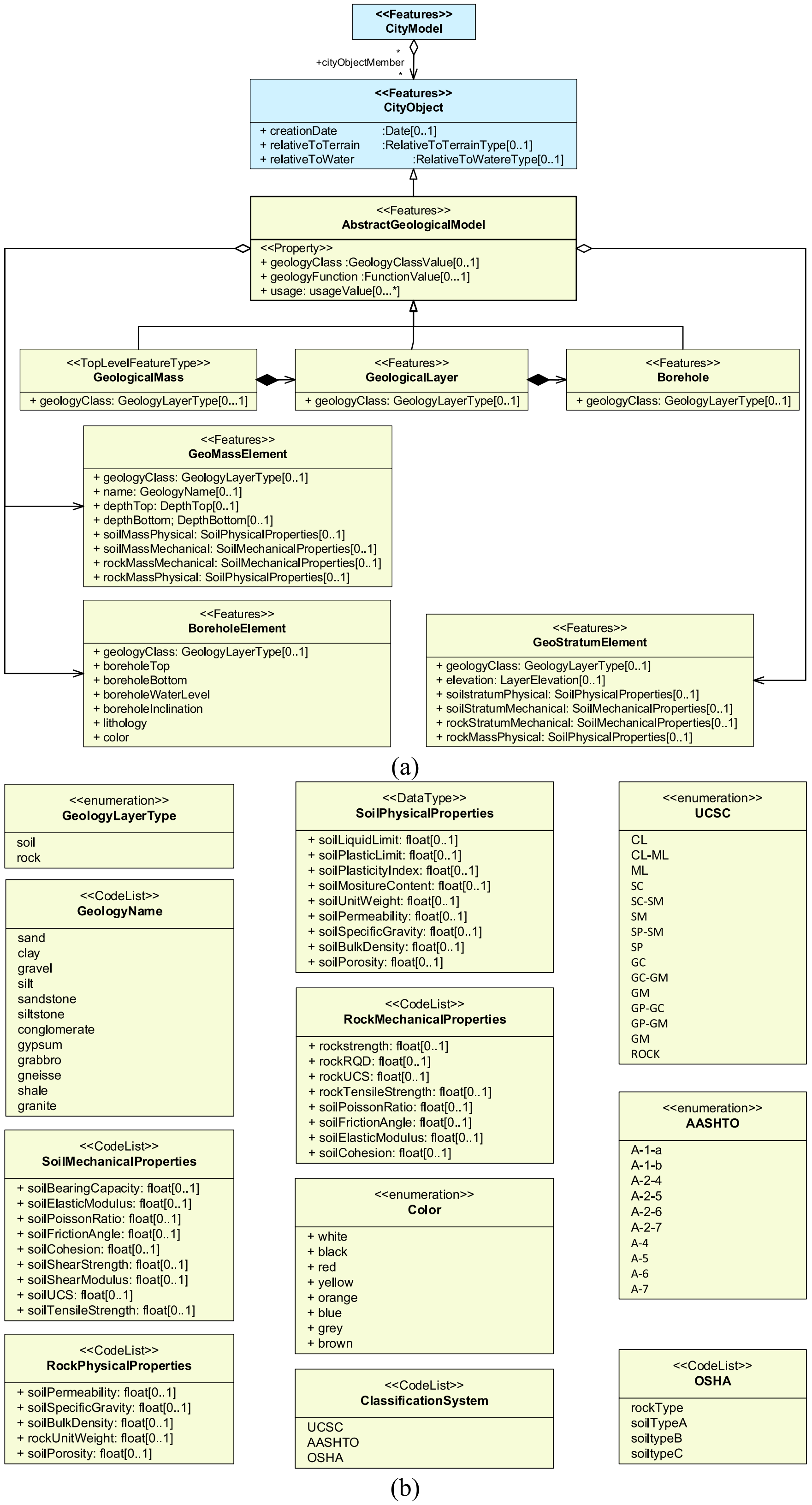


Fig. 11. Unified Model Language (UML) diagram of the proposed CityGML ADE for the Geological Model.

5.3. Voxels generation on meshes

The final step is the generation of voxels on the meshes. Voxelization is the process of converting meshes into the voxels (Shoaib Khan et al., 2021; Wang et al., 2020). The study uses identical-size voxels and they are created for each selected geological mesh. The size of voxel is decided for each geological mesh, which in turn depends on the properties of the geological materials that is coming from the geological

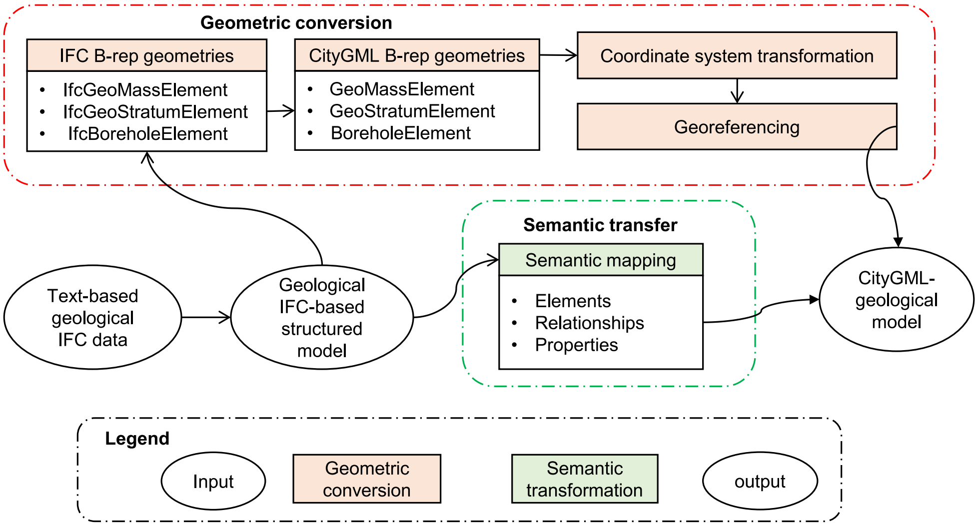


Fig. 12. IFC to CityGML integration tasks.

Table 3
Mapping classes between IFC and CityGML and their representation.

IFC Entity	Representation	CityGML Entity	Representation
IfcGeoMassElement	B-rep	GeoMassElement	B-rep
IfcGeoStratumElement	B-rep	GeoStratumElement	B-rep
IfcBoreholeElement	B-rep	BoreholeElement	B-rep

investigation reports and exploratory data.

When a geological mesh is selected for the voxelization, the algorithm creates an axis-aligned bounding box around the mesh. The bounding box closes the mesh object and utilized for testing. The mesh geometry is surrounded by a bounding box and the geometrical properties of the bounding box are retrieved such as diagonal, center, area, volume, etc. The geometrical features of the bounding box are used for voxel creations. The diagonal vector of the bounding box was calculated using the vertex coordinates of the meshes, which represents the size of the bounding box. The diagonal vector has been deconstructed/divided into several points. The division of the diagonal vector depends on the inhomogeneity in the geological condition. Each point of the diagonal vector has coordinates such as xi, yi, zi. Using the coordinates of points, vector planes are constructed. The points and the corresponding vector planes are projected in each direction of the bounding box, meaning that adaptive points are created to host the voxels.

The voxelization of the bounding box is created in three steps; (i) center voxel creation, (ii) cross-referencing in U-direction, (iii) cross-referencing in V-direction, and (iv) cross-referencing in W-direction. This process has been illustrated in Fig. 8. To initiate the voxelization, a cube/voxel has been generated on the center point of the diagonal vector. The center voxel play a key role, since the voxelization of the geological mesh is obtained using center voxel by mean of sharp transition (Fig. 8). The center voxel size is selected based on the geological properties particularly the inhomogeneity level of the geological model. The center voxel is translated into the generated adaptive points resulting in the voxelization of the bounding box.

Firstly, the center voxel is translated into the U-direction that generates voxel of the specific size in the U-direction (Fig. 8b). Similarly, the voxels are generated in V-direction resulting in the voxelization of a plane (Fig. 8c). Finally, the voxels on a plane are translated in the W-direction in the positive and negative direction that results in the voxelization of the referenced bounding box (Fig. 8d). However, the boundary of a bounding box do not necessarily match the boundary of the geological mesh because the bounding box has a cubical shape while geological properties represented by a geological meshes varies. It causes the creation of extra unnecessary voxel. Also, the boundary of each geological mesh is important to the engineers and project managers. To address this, a collision test has been performed that removes voxels outside the mesh geometries. Finally, the voxel size is verified according to the condition of the ground. If the voxel size is inefficient to the inhomogeneous geological condition, an iteration is performed. The attributes information is assigned to the voxel-based geological model.

6. IFC and CityGML extension for geological data

6.1. Extension of IFC for the geological model

The existing IFC was first constructed for buildings. It now includes infrastructure, such as tunnels, bridges, and railways, to support interoperability during various construction phases. However, the definition and structure of geological models are still lacking in the existing IFC. This study extends the IFC entities to geological models. The latest version of the IFC 4 × 3 was used as a base for the extension of the geological entities. To extend and add IFC entities to geological models, it is essential to represent the characteristics of the geological model according to the IFC object-oriented structure. For example, (i) defining the spatial structure of the geological model; (ii) the elements necessary to represent the full feature of the model while using a minimum number of IFC objects to avoid unnecessary expansion and information; (iii) identifying the properties of the geological elements, such as the physical and mechanical characteristics of the geology described by parameters; and (iv) defining the relationship between the spatial entities of the geological model and relating the spatial entities with the geological elements.

6.1.1. Spatial structure of the geological model

Fig. 9a presents the definition of the spatial structural entities added to the IFC structure specifically to represent the geological information, namely, IfcGeologicalModel from the abstract super-type IfcExternalSpatialStructureElement. The IfcExternalSpatialStructureElement defines the different kind of external spaces, regions, and volumes, while IfcGeologicalModel presents the spatial structural entities specifically to represent the geological entities. Based on the proposed geological data model (Fig. 3, section 3.2), the spatial structure of the geological model was divided into geological bodies, layers, and boreholes. IfcGeologicalBody, IfcGeologicalStratum, and IfcBorehole are conceptual entities defined to complete the IfcGeologicalModel. Additionally, a geological body represents the space or volume of a geological model. Moreover, IfcGeologicalStratum defines the variation of the geological layer, and

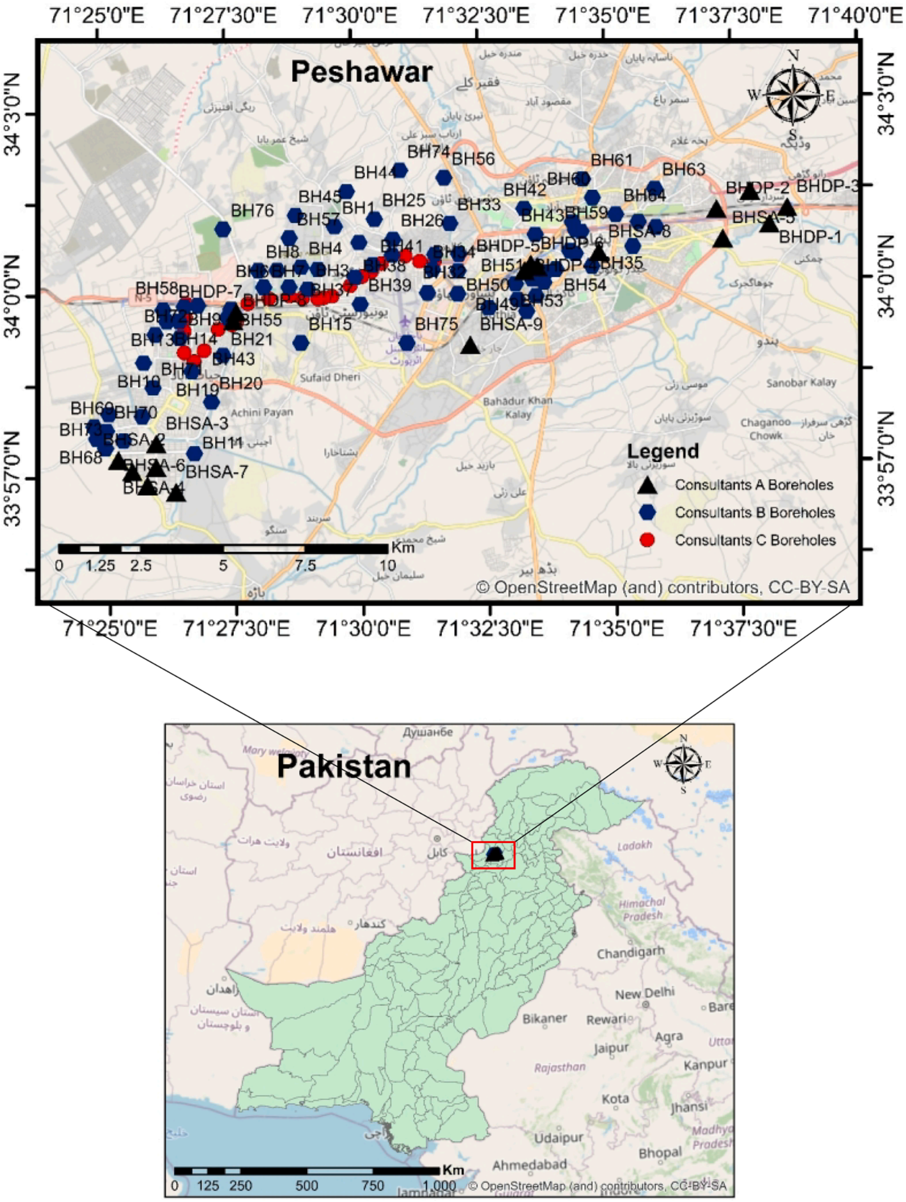


Fig. 13. Location map of the case study and boreholes location.

IfcGeologicalBody is composed of a single or many IfcGeologicalStratum. Finally, the IfcBorehole defines the linear feature at a point in the geological space. IfcGeologicalStratum is aggregated from the same type of IfcBorehole, and a single borehole can be aggregated from many borehole segments. The enumeration differentiates between the different types of geology.

6.1.2. Physical elements of the geological model

The abstract super-type IfcGeologicalModelElement was added using IfcCivilElement. IfcCivilElement was inherited from IfcElement, defining elements related to civil engineering applications. The newly proposed entity, IfcGeologicalModelElement, defines all geological elements in the geological model. Fig. 9b presents the hierarchical relations and extension of IfcGeologicalModelElement. The IfcGeoMassElement, IfcGeoStratumElement, and IfcBoreholeElement were added as subclasses of the IfcGeologicalModelElement. IfcGeoMassElement represents the geological elements available in a geological body. Different types of geological bodies were categorized based on their enumeration. For instance, IfcGeoMassElementEnum distinguishes cavities from geological soil or rock layers. Furthermore, IfcGeoStratumElement defines the geological layers present in the underground space of a specific type. The types of layers are categorized using enumerations such as clay, gravel, and rock layers.

6.1.3. Relationship between proposed entities

The relationships between the proposed entities are defined (Fig. 10). It includes the association between the spatial structural entities and the relationship that relates them to the physical entities. The spatial entities were related to each other using IfcRelAggregates. The IfcRelAggregates uses the entire concept and related parts, such that the entirety is made up of parts. Hence, IfcRelAggregates state that the IfcGeologicalModel is aggregated from the IfcGeologicalBody, IfcGeologicalStratum, and IfcBorehole. Moreover, one IfcGeologicalBody can have one or many IfcGeologicalStratum, and the IfcGeologicalStratum can have single or multiple strata. Furthermore, the spatial structural elements were related to the physical elements using the IfcRelContainedInSpatialStructure. For example, IfcGeologicalStratum is related to IfcGeoStratumElement by IfcRelContainedInSpatialStructure.

Table 4
Structure of the information stored in the database (only three boreholes).

Location ID	Easting	Northing	Depth Top	Depth Bottom	Geology (UCSC)	SPT(In-situ)	Friction angle (ϕ)
BH1	730,232	3,766,872	0	1	Silty clay (CL)	Lose filling	18
			1	2	Silty clay (CL)	30	21
			2	3	Silty clay (CL)	29	21
			3	4	Silty clay (CL)	34	22
			4	5	Silty clay (CL)	33	19.6
			5	6	Silty clay (CL)	33	18.4
			6	7	Silty clay (CL)	28	22
			7	8	Silty clay (CL)	38	21.7
			8	9	Silty clay (CL)	48	20.8
			9	10	Silty clay (CL)	52	23.6
BH2	729,424	3,764,966	0	2	Clayey gravel (GC)	refusal	18.3
			2	4	Silty clay (CL)	13	19.7
			4	6	Silty clay (CL)	12	21
			6	8	Clayey gravel (GC)	17	23
			8	10	Clayey gravel (GC)	14	22.6
			10	12	Clayey gravel (GC)	13	20.5
			12	14	Clayey gravel (GC)	19	22.3
BH3	727,915	3,765,531	0	2	Silty clay (CL)	15	25.2
			2	4	Silty clay (CL)	12	19.3
			4	6	Clayey gravel (GC)	18	19.5
			6	8	Sandy gravel (GP)	16	20.5
			8	10	Sandy gravel (GP)	16	21.8
			10	12	Sandy gravel (GP)	15	22
			12	14	Sandy gravel (GP)	21	24.6

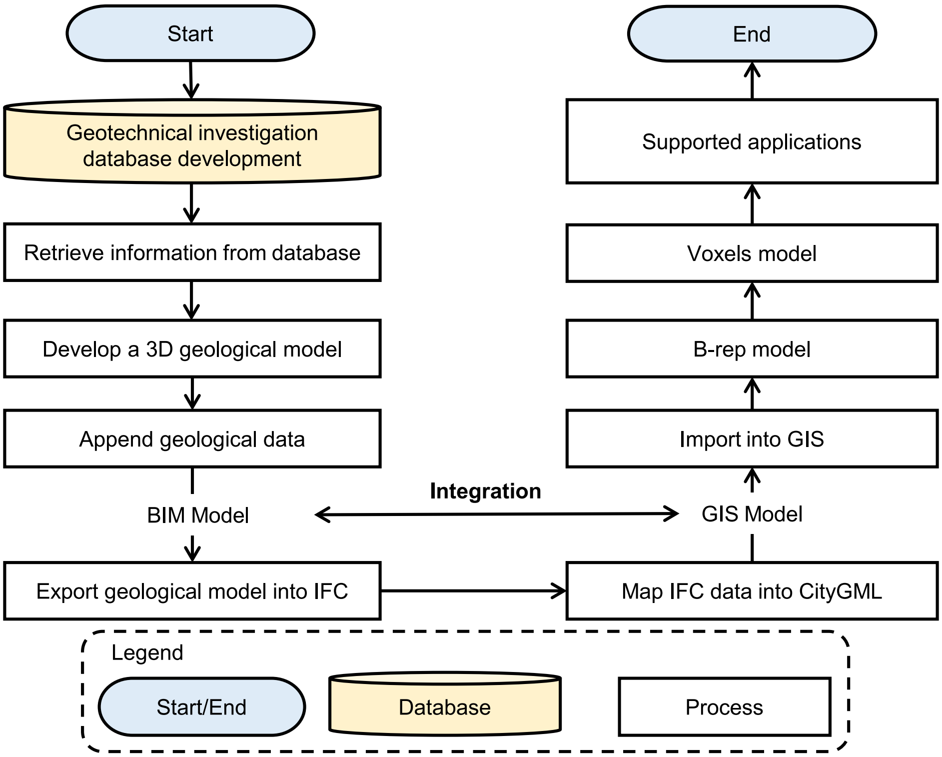


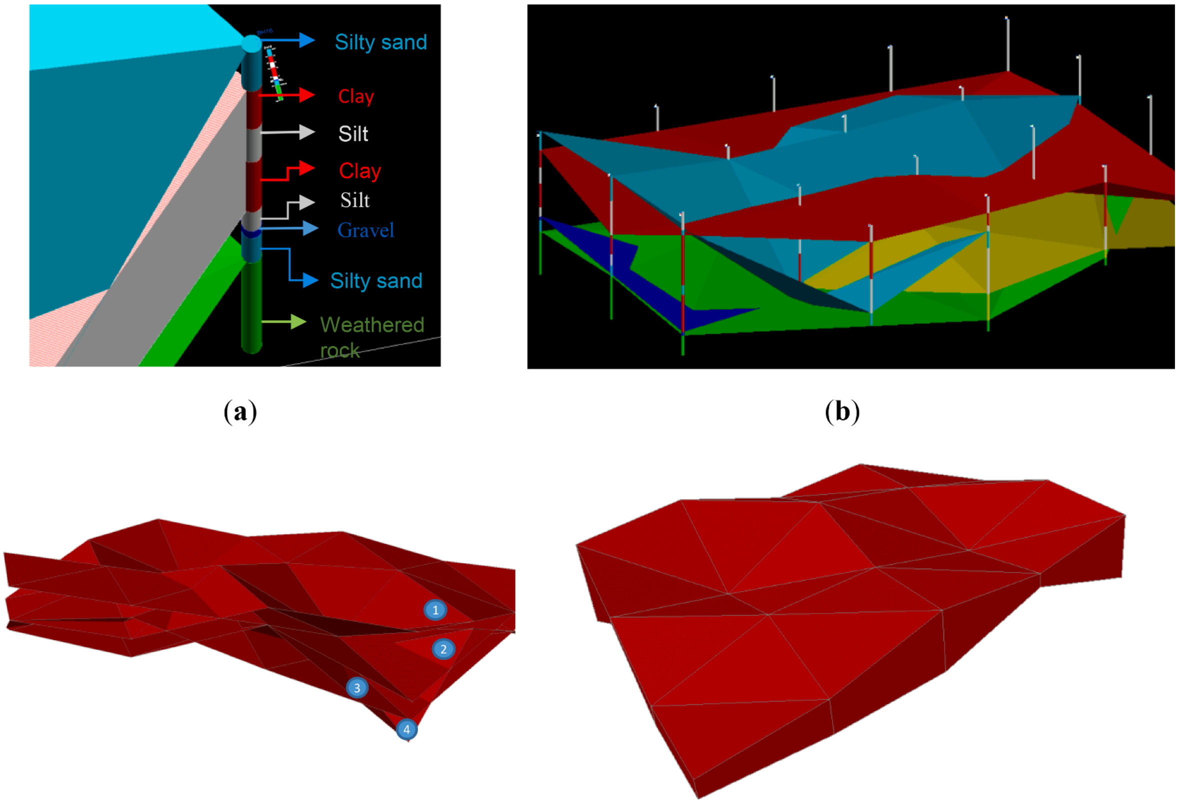
Fig. 14. Workflow for the implementation of the proposed framework for the case study.

6.1.4. *Properties of the geological elements*

The properties of the proposed geological and physical elements were defined by extending IfcPropertySet. The IfcPropertySet can hold all properties of the elements in a property tree. The properties were defined for each geological element with a specific string name. The value of a property was stored and defined by the IfcPropertySingleValue. For example, the properties of IfcGeoMassElement are categorized into common, physical, and mechanical properties included in the IFC using the IfcPropertySet. The IfcPropertySet includes an element's set of parameters, and each parameter's value is supported using the IfcPropertySingleValue. Definitions of the parameters specific to the geological elements proposed in this study are listed in Table 2.

6.2. *Extension of CityGML for the geological model*

In this study, a geological model, ADE, was proposed. Geological



(a) (b) (c) (d)

Fig. 15. Developed Geological Model: (a) IfcBorehole visualization enumerating various geology types; (b) developed IfcGeologicalStratum; (c) enumerated clay stratum from the study area; and (d) IfcGeologicalMass representing the available clay.

feature classes with properties, data types, code lists, and relationships are significant for representing geological information. Fig. 11 illustrates the proposed ADE to represent geological information in CityGML using the UML model. Following the geological model, additional classes were added to CityGML to represent geological data. The Abstract Geological Model is an abstract superclass that shows all types of engineering geological features in underground space. The top-level feature of the geological model is geological mass, which denotes the principal components of the proposed conceptual model. It is further decomposed into the geological layer and borehole because the geological mass comprises one or more geological layers. The different geology types were defined using enumeration, such as the geology type being either soil or rock (Fig. 11b). In addition to the composition, the geological model contains geological elements categorized based on their attributes. For example, a code list further divides the geological type into different soil and rock types. The UML model contains all the necessary information to represent the geological information in the GIS environment using open standard CityGML.

6.3. *Integrated BIM-GIS platform for geological model*

The IFC to CityGML integration must convert the geometric and semantic information (Fig. 12). The integration tasks in achieving BIM-GIS integration for geological model includes; (i) IFC data extraction; (ii) representation conversion; (iii) coordinate system transformation; (iv) georeferencing; and (v) semantic mapping.

First, the IFC file is extracted that contains geometric and semantic information. A text-based IFC file is extracted that contains significant information. The information necessary according to the proposed geological data model is filtered. Second, the geometries are converted from the IFC to the CityGML. The geometry conversion is greatly affected by the representation in IFC and CityGML. In our proposed model, the geometries on both BIM and GIS are represented with the B-rep, making the geometric conversion efficient without losing geometrical information and going through the time-consuming geometrical transformation. However, it should be noted that the exported file size and system specification play a key role when a geological model is exported as B-rep considering IFC as export format. The file size depends on the number of B-rep geometries in the BIM model. In case of huge file having high number of B-rep geometries, the model is divided into multiple units. Each unit is exported separately that reduces the file size and make it efficient to work with the IFC file.

The semantic mapping matches the geological elements, their properties, and relationships among them. The extended IFC and CityGML classes are based on a common geological data model that has an advantage because the elements and relationships in both schemas are similar. For example, the entity IfcGeoMassElement from the extended IFC is mapped to the extended CityGML GeoMassElement, because both entities in different schemas represent the same feature.

Third, BIM and GIS use different coordinate systems. BIM uses a local coordinate system, whereas GIS uses a geographic coordinate system. Many researchers have solved this task, and their proposed method has been used in IFC to CityGML mapping (Deng et al., 2016). IFC 4 includes an entity, IfcMapConversion, used to georeference the IFC data in the GIS for georeferencing. Table 3 presents the details of the mapping classes between IFC and CityGML.

7. Implementation of the proposed BIM and GIS framework

7.1. *Geotechnical data collection and database development*

The proposed framework is demonstrated using the geotechnical investigation data of Peshawar City, Pakistan. Fig. 13 shows the location of Peshawar on the world map and the geolocation of the points where

Table 5
Part of the IFC file representing entity definition, entity representation, IfcProperty Set, IfcPropertySingleValue, and relation exported from Rhino 3D and Autodesk Civil 3D.

IFC Export from Rhino 3D

```
/* Entity Definition */
  #618 = IFCFACETEDBREP(#41);

  /* Entity Geometric Representation */
  #619 = IFCSHAPEREPRESENTATION
  (#14,’Body’,’Brep’,(#618))

  /* Properties*/
  #620 = IFCCURVESTYLE($,$,
  IFCLENGTHMEASURE(0.0001),$);
  #621 = IFCCOLOURRGB($,0.,1.,0.);
  #622 = IFCFILLAREASTYLE($,(#621));
  #623 = IFCSURFACESTYLERENDERING
  (#624,0.,$,#625,$,#626,$,
  IFCSPECULAREXPONENT(25.6)
  ,$);
  #624 = IFCCOLOURRGB($,0.,1.,0.);
  #625 = IFCCOLOURRGB($,1.,1.,1.);
  #626 = IFCCOLOURRGB($,1.,1.,1.);
  #627 = IFCSURFACESTYLE($,.BOTH.,
  (#623));
  #628 =
  IFCPRESENTATIONSTYLEASSIGNMENT
  ((#620,#622,#627));
```

a. IFC Export from Rhino 3D

```
/* Entity Definition */
# 23772 =
IFCBUILDINGELEMENTPROXY
(’2L9OjMv$6oRm0000000BHm’,
#59,$,$,$,#23774,#23779,$,$);

/* Entity Geometric
Representation */
#23781 =
IFCSHAPEREPRESENTATION
(#276,’Body’,’Brep’,(#24156));

/* Property Set Definition for
Mechanical Properties Category
*/
# 24169 = IFCPROPERTYSET
(’0bPN5asAX1iueVh0$IWMDi’,
#59,‘mechanical properties’,$, (#
24171,#24173,#24175,#24177,
#24179,#24181));

/* Mechanical Properties*/
# 24171 =
IFCPROPERTYSINGLEVALUE (‘
Cohesion’, $, IFCLABEL(’90′),$);
# 24173 =
IFCPROPERTYSINGLEVALUE
(’Shear strength’,$,$,$);
# 24175 =
IFCPROPERTYSINGLEVALUE
(’Compressive strength’,$,$,$);
# 24177 =
IFCPROPERTYSINGLEVALUE
(’Angle of internal friction‘,$,
IFCLABEL(’30′),$);
# 24179 =
IFCPROPERTYSINGLEVALUE
(’Poisson’s ratio’,$,$,$);
# 24181 =
IFCPROPERTYSINGLEVALUE
(’Elastic Modulus’,$,$,$)

/* Relating Property Set to
Geotechnical Element */
# 24183 =
IFCRELDEFINESBYPROPERTIES
(’0Ncg4oPQ5218Sxdpx911ds’,#59,
$,$,(#23772),#24169);
```

the geological data have been collected.

The geological data collected from the site included borehole data, in-situ test data, and laboratory test data. One hundred fourteen borehole data points and the corresponding in situ and laboratory test data were collected from geotechnical laboratories and local consultants. This study used all these geotechnical data parameters to apply the proposed framework. The data contain the coordinates of each borehole location, the depth of each borehole, the soil type, the depth at different intervals collected during the drilling process, and the corresponding in-situ and laboratory test parameter data. Table 4 lists some boreholes along the depth used in the case study.

7.2. Geological model development

The steps involved in developing the integrated geological model for the case study are demonstrated in Fig. 14. The implementation steps include developing a geotechnical database, 3D geological model development, extraction of an IFC-based structured model, integrating with CityGML, achieving a voxel-based model, and applying the developed model.

First, a database was developed for the data collected from different consultants. The database contains spatial, semantic, and geological condition data for each known point (borehole location). Each point has a unique ID and location coordinates, such as easting, northing, geology type, and depth because the information has been collected at different intervals along with the depth, interval length, UCSC codes corresponding to each geology type, orientation, inclination, in-situ parameters data, such as SPT, and laboratory test parameters, such as liquid limit, plastic limit, bearing capacity, shear strength, and other geological parameters.

The data stored in the database developed in the previous step were used to develop a geological 3D model for Peshawar City using the developed algorithm (Table 1). The algorithm was implemented in Dynamo, and Autodesk Civil 3D 2021 was used as the 3D viewer. The database data contained the location information corresponding to each borehole. The WGS84 datum was used for the case study implementation. Defining a coordinate system in the initial stages of modeling is crucial because it is used to transform the model from BIM to GIS for integrated model development. Autodesk Civil 3D software supports the definition of a coordinate system. The application of the coordinate system makes it easy to map the model entities from IFC to CityGML in the later stages.

When geological data are input into the BIM tool, it creates a coordinate geometry (COGO). Therefore, each borehole point has corresponding COGO points that present a 3D visualization of the borehole and depth. These 3D points are not limited to 3D visualization; other non-geometric semantic information is also attached. A single borehole modeled in BIM is categorized into multiple segments depending on the strata of the ground.

Borehole visualization is shown in Fig. 15a. A single borehole contains five strata: silty sand, silt, clay, gravel, and weathered rock. Different colors represent each type of soil. The IfcBorehole entity was used to represent the borehole data, and each segment of the borehole exhibiting different soils was differentiated by enumeration. The points representing the same geological types were interpolated to form a geological stratum (Fig. 15b). In the context of this research implementation, a spatial interpolation technique, triangular irregular network (TIN) method has been used**.** There are several reasons that we choose this interpolation method for the implementation. Firstly, this method provides a simple way to interpolate and model the geological features. Secondly, the model is accurate and easy to update if the data is changed or updated. Most importantly, it is available in the BIM and GIS software and takes less computational time. For example, in Fig. 15c, the clay top points were combined to form a geological clay stratum, and the IfcGeologicalStratum entity was used to store the data. Different types of strata were categorized using enumeration. Each stratum is appended to information specific to the geological stratum (Table 2). A geological mass was obtained from the geological stratum, sharing a common enumeration (Fig. 15d). It was obtained by overlaying the two surfaces of the same geological type by vertical projection in a horizontal plane. Each geological stratum has variation that can be seen in Fig. 15c, 15d. The top and bottom surfaces in Fig. 15c are composed of several composite triangles. A truncated prisms are extracted that shows the volumetric information. For example, clay stratum are aggregated to form a clayey geological mass. The clayey stratum 1,2,3, and 4 shown in Fig. 15c sharing a common enumeration are overlaid on each other and prisms are extracted according to the method explained in Fig. 5d. The IfcGeologicalMass was used to store geometrical and semantic geological mass data.

According to the proposed IFC data model, all geological information is stored in an IFC-based schema. The IFC file was extracted from the BIM tool containing all geological entities, their geometric representation, relationships between entities, and the semantic information attached to each entity. Each entity has a unique ID, called a global unique identifier (GUID). However, a BIM tool that does not conform to

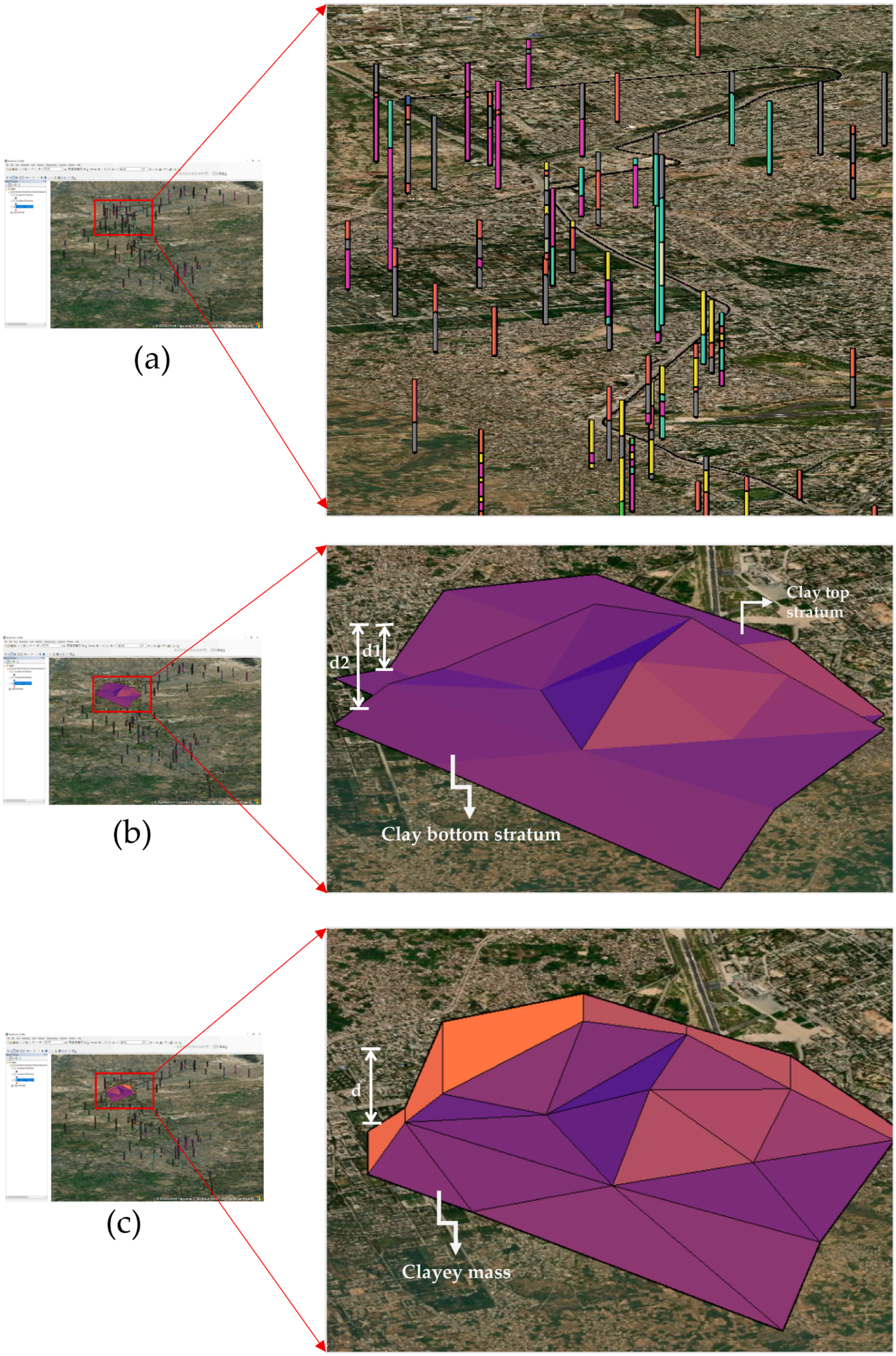
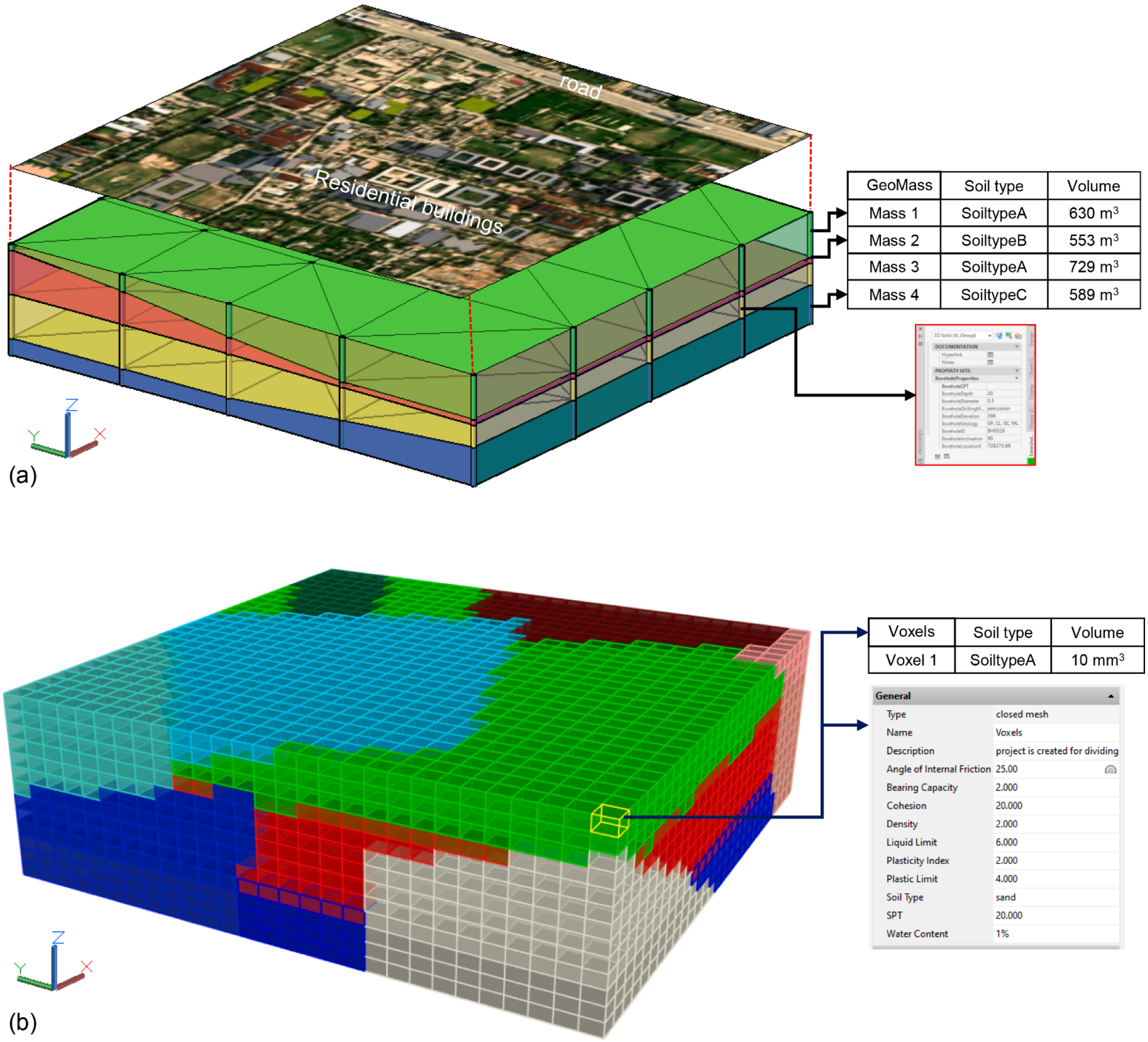


Fig. 16. Geological model visualization in the GIS environment: (a) BoreholeElement visualization (114 boreholes visualized in the left window, some are visualized by zooming for better visualization at right); (b) GeoStratumElement entities in the GIS (some layers in (b) are kept hidden for clear visibility); and (c) Clayey mass visualization, (perspective view from bottom to east for (a), (b), (c)).

IFC 4 × 3 exports the IFC elements as "IfcBuildingElementProxy". The two most common and widely used software that export the geological features in B-rep based IFC are Rhino 3D and Autodesk Civil 3D. Both of these software can model geological entities and export it into the IFC format. Rhino 3D models the geological entities using surfaces and polysurfaces, which are considered as B-rep geometries. Furthermore, Rhino 3D uses a plugin called VisualARQ that includes built-in IFC import and export option and make it possible to exchange the Rhino 3D geometries and semantic in the IFC format. So, when a geological model using B-rep geometry is constructed in Rhino 3D, it is exported automatically into the B-rep based IFC using VisualARQ tool. The part a in Table 5 present an example of the export of a geological entity from Rhino 3D into the B-rep based IFC. On the other hand, Autodesk Civil 3D also have built in IFC import and export options that provides functionality to exchange the models in the IFC format. When a geological model is constructed in Autodesk Civil 3D using Civil 3D surfaces and extracted solids from the surfaces that represents the geological masses, it is exported automatically into the B-rep based IFC during the IFC export. Table 5 presents a part of the representation of the geological entities in the text-based IFC from Rhino 3D and Civil 3D software.

The extracted IFC contains information regarding the coordinate system and georeferencing entities. In addition, the IFC entities were represented using B-rep, as shown in Table 5. Finally, the IFC elements were mapped to CityGML elements followings the steps discussed in the



GeoMass	Soil type	Volume
Mass 1	SoiltypeA	630 m^3
Mass 2	SoiltypeB	553 m^3
Mass 3	SoiltypeA	729 m^3
Mass 4	SoiltypeC	589 m^3

3D Solid (4) (Group)

DOCUMENTATION

Hyperlink	
Notes	

PROPERTY SETS

BoreholeProperties

BoreholeCPT	
BoreholeDepth	20
BoreholeDiameter	0.5
BoreholeDrillingM...	percussion
BoreholeElevation	368
BoreholeGeology	GP, CL, GC, ML
BoreholeID	BH0028
BoreholeInclination	90
BoreholeLocationX	728275.69

Voxels	Soil type	Volume
Voxel 1	SoiltypeA	10 mm^3

General

Type	closed mesh
Name	Voxels
Description	project is created for dividing
Angle of Internal Friction	25.00
Bearing Capacity	2.000
Cohesion	20.000
Density	2.000
Liquid Limit	6.000
Plasticity Index	2.000
Plastic Limit	4.000
Soil Type	sand
SPT	20.000
Water Content	1%

Fig. 17. (a) Application of the developed model provides color-coded visualization of the geological boreholes, layers, and masses in 3D underground space, the volume of each available underground mass, and classification of the developed model into three zones (perspective view looking from above to the East), and (b) voxel-based model representing micro-level detailed information.

Table 6
Evaluation of the proposed BIM-GIS integrated framework.

Qualitative Matrices	Propose BIM-GIS Geological Data Management	Traditional Geological Data Management
Visualization	Detailed	Basic
Inhomogeneous information	Supported	Not supported
Data exchange	Supported	Not supported
Communication	Effective	Ineffective
Volume calculation	Automated	Manual
Material information	Detailed	Basic
Decision support	Easy	Difficult
Model update	Quick	Time-consuming
Accuracy	High	Medium
Coordination	Efficient	Inefficient
Data format	Unified	Multiple
Flexibility	High	Low
Computation	Intensive	Less
Complexity	High	Low
User satisfaction	High	Medium

method section. The IFC entities share the same representation as CityGML (Table 3 in Section 3.5). Therefore, the entities were not geometrically transformed. Fig. 16 shows the visualization of the geological data in the GIS environment. It represents the geological information from bottom to east for better visualization.

It integrates the geological model with current contextual information, such as buildings, roads, bridges, and other infrastructure. Fig. 16a visualizes the borehole elements of CityGML in the GIS environment that visualizes the geology at a single point. The top of the borehole was attached to the ground surface, and variations in the geology were visible. Meanwhile, Fig. 16b and c demonstrate the geological condition over the area or volume where clay layers are visualized in the underground space. The depths of the visualized clay layers are d1 and d2, meaning that the first clay layer available in the underground space has an elevation of d1, and the second layer is d2. All geological attributes were listed when the model elements were selected, making it an information-rich model.

The integrated BIM-GIS geological model is shown in Fig. 17a. The developed model contained geometrical, semantic, and spatial information. Geometric information provides the variation in the vertical borehole in 3D space, geological stratum, and geological masses. The different types or enumerations of geology are represented using different colors. From Fig. 17a, different geological layers can be differentiated. For example, the sandy gravel available at the top is depicted in green. The color-coded visualization of geology in a 3D scene makes it very effective for planners and engineers to make critical

Table 7
Survey details.

Questions	Highly agree	Agree	Neutral	Disagree	Highly disagree
Is the BIM-GIS integrated framework useful for city-level geological data management?	53.8%	36.2%	10%	0	0
Can the city-level geological data management help in better infrastructure planning?	62.4%	22.7%	14.9%	0	0
Would the proposed common data model help project participants in the city-level geological data management?	71.4%	19.5%	9.1%	0	0
Can the BIM-GIS framework improve the visualization and analysis of geological data?	58%	22.7%	15.3%	4%	0
Does the voxel-based representation provide better visualization at a different scale?	70%	11%	19%	0	0
Can voxels represent inhomogeneous micro-level information?	78.9%	6.8%	14.3%	0	0
Do the BIM-GIS integrated model support efficient data retrieval and update?	40.4%	55%	4.6%	0	0
Can the proposed framework improve geological information exchange?	66.3%	23.9%	6%	3.8%	0
Is the volume calculation from the proposed model helpful?	46.7%	32%	13.3%	4%	4%
Can the BIM-GIS geological model help in decision support?	51%	33.3%	15.7%	0	0
The accuracy of proposed model is improved using proposed model?	59%	31%	10%	0	0
The data exchange has been improved with the use of IFC and CityGML?	46.9%	31.3%	15%	6.8%	0
The proposed model is flexible to capture required complexity?	54.9%	25.5%	13.76%	5.84	0

decisions.

The B-rep model representing homogenous information of a geological mass has been converted into voxels to include inhomogeneous information. The geological masses are converted into voxels according to the developed algorithm (Fig. 7, Section 5). Firstly, each of the geological masses are converted into geological meshes. The geological meshes are used as an input to the developed algorithm. Secondly, the size of the voxel is selected based on the inhomogeneity in the geological masses. Smaller size voxels are used in the inhomogeneous region, while bigger voxels are selected to represent the homogenous region. Finally, the geological meshes are converted into voxels using the developed algorithm. Moreover, semantic information are assigned to each of the voxel. The voxel model (Fig. 17b) contains more detailed information than the B-rep model (Fig. 16a). Each voxel contains geometric, semantic, and spatial information. The size of voxels varies depending on the geological condition of the area. The color of the voxel can be selected for each attribute. The color variation on a small voxel-level makes the geological model much smarter for the construction managers, urban planners, engineers, and geologists to make critical decisions. The information carried by each voxel can be efficiently retrieved for engineering purposes. For example, user-defined rules can be applied to determine the suitability of a site for safe construction.

The major advantage of the proposed data model and algorithms is to develop an automated 3D geological model with a boundary and voxel model. The demonstration of the proposed method in a case study revealed that the boundary and voxel model can efficiently represent the geological information in the BIM-GIS 3D environment. Most importantly, the inhomogeneous geological information are efficiently represented with the voxels.

7.3. Benefit assessment of the proposed method

The benefits of the proposed method were assessed using two methods. Firstly, the proposed method was compared with the traditional one considering some key parameters. Secondly, it has been evaluated by the professionals involved in activities that need geological models, such as civil engineers, architects, urban planners, geologists, etc.

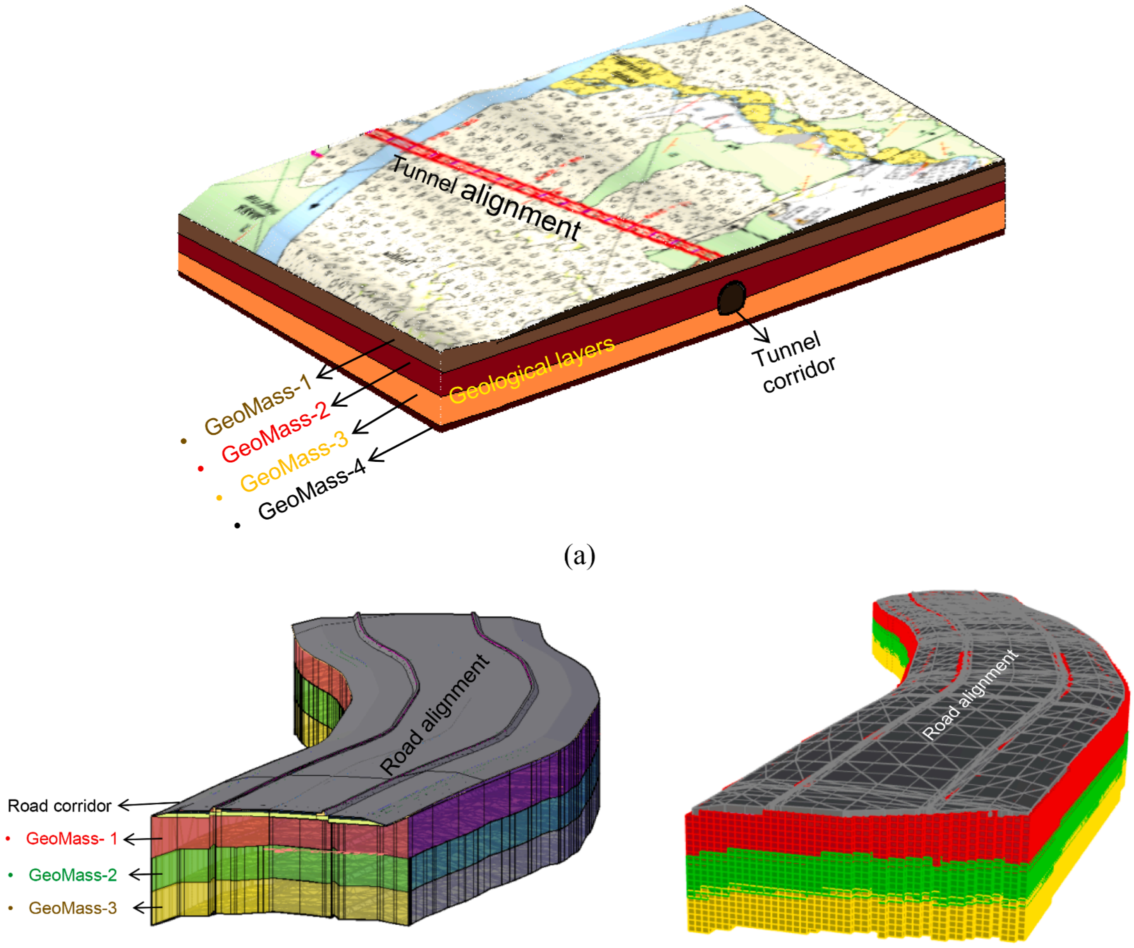
The research team evaluated the proposed method using a case study and compared it with traditional methods (Table 6). The qualitative metrics present a comparison between the proposed method and traditional methods. It has been revealed that the proposed method provides better visualization than traditional methods. The visualization scenarios can be changed to a different scale from macro-level to micro-level. For example, B-rep or larger voxels can be used for small details, and smaller voxels can be selected that provide much better and more detailed visualization. Voxel-based models are well-suited for representing volumetric data. They can capture fine details in complex geological structures and are useful for operations such as surface extraction and volume rendering. Voxel-based models can represent geological structures as a series of three-dimensional pixels, allowing for a more accurate representation of complex geological structures.

The resolution of the models is an important factor to consider. Voxel-based models resolution can be changed according to the geological condition that is higher than that of traditional models, which could result in more accurate and detailed representations of the geological structures. Voxels can capture complex geological features since the proposed model allows to select different voxel sizes and better suited. Voxel-based models are computationally intensive due to their high resolution in representing the fine and complex geological features. Additionally, voxels are providing more accuracy specifically in areas where the geological structure is complex and irregular.

The data exchange process was standardized based on unified data models (IFC and CityGML) to enhance stakeholder communication. The volume of a geological mass can be easily calculated in an automated manner compared to traditional methods. The proposed system supports semantic information, quick model updates, and decision making. The BIM-GIS integrated approach based on unified data models is highly recognized and acknowledged to benefit geological data modeling and management for large areas. Overall, our results show that the proposed geological models created by our algorithm are comparable in quality to traditional models providing advantages and can be useful for a wide range of applications.

A survey was conducted with potential users for detailed assessment and verification of the proposed framework. This survey included senior consultants, contractors, civil engineers, geologists, planners, and construction managers. The questionnaire included ten questions that the participants had to assess and rate their agreement level.

From Table 7, the overall feedback of the participants was positive. The participants agreed that BIM-GIS was required for city-level geological data management. This will help stakeholders model, manage, retrieve, and update underground data at any stage of the



(a)

(b)

(c)

Fig. 18. (a) Visualization of the geological layers with the surface and underground tunnel model; (b) Visualization of the geological layers and masses with the road corridor; and (c) voxel-based representation of the geological condition along the road corridor.

construction project. Support for using the developed model for infrastructure planning has also received approval. For example, the GIS environment integrates the geological model with surrounding urban layers, such as buildings, utility networks, and other infrastructure. The integrated 3D model provides a clear understanding of geological features in large areas that can be utilized during the planning, design, and construction stages. For example, tunnel infrastructure is an underground structure with complex geological features around the structure. The proposed methodology can help better understand the geological features along the corridor (Fig. 18). Some participants were chosen from Peshawar, Pakistan (the case study location). The participants used the model developed for already-constructed buildings and roads. The recently constructed Bus Rapid Transit (BRT) road was used as a case scenario for the infrastructure (Fig. 18b, c). While several buildings designed by the designer in the survey verified the model. It has been identified that the proposed framework and model are beneficial in selecting a safe location or infrastructure route and will be useful in future infrastructure planning.

Visualizing geological surfaces and masses on a city level with different resolutions makes it very effective for decision-making. The voxel-based representation that can incorporate small-scale and inhomogeneous information provides an innovative solution. Furthermore, refining voxels into different scales and incorporating several geological properties make it very effective for the managers to perform analysis. The participants added additional borehole data to the existing model to verify the model updates and information retrieval functions. It is acknowledged that the model can be updated efficiently.

Meanwhile, a few participants pointed out that volume calculation may not be helpful. However, these participants primarily focused on the superstructure design team. In contrast, most participants agreed that the volume calculation of the underground geological layers at the city level would help the project participants, specifically in the case of unstable soil layers. For example, if a peat layer is available in an underground space, the proposed method can be used to calculate peat volume. Similarly, other contamination that is sometimes available in the underground space in a very small amount can be effectively represented and visualization with the voxels.

Overall, the participants' feedback demonstrated that the proposed geological data model improved the efficiency of geological data management. There were some suggestions regarding developing a prototype and mobile development for the output geological model visualization and analysis, which will be considered in future research.

8. Conclusion

Geological information is essential and plays a significant role in a project's planning, design, and construction stages. However, it is managed by heterogeneous data models characterized by a 2D representation that lacks a unified format. The geological data primarily varying in a horizontal and vertical direction is modeled using homogenous representation. The existing models either lack 3D volumetric information or are integrated 3D models that cannot be refined into smaller sizes to include the inhomogeneous geological data. Furthermore, the traditional system exchanges geological information among stakeholders in different formats. In most construction projects, geological information remains unknown to project managers, leading to ineffective decision-making. Planning and making critical decisions would be very easy if project planners and managers understood the subsurface geological data. Therefore, a new method is urgently required to efficiently model, store, manage, exchange, and update 3D geological data in a unified format.

This study proposed a boundary and voxel-based geological model using the BIM-GIS framework to model and manage geological information. The current IFC and CityGML schemas lacked geological entities. Hence, this study developed a geological data model that extended the current IFC and CityGML schema by proposing geological ADE to include geological data in the BIM and GIS environment. The data between BIM and GIS was transferred through schema mapping, i.e., IFC-to-CityGML mapping. Algorithms that efficiently create a boundary and voxel-based geological model were developed. The proposed boundary and voxel-based model support the homogenous and inhomogeneous geological information. The developed data model contained all the necessary information regarding the geological conditions. The proposed system was demonstrated using geotechnical data of Peshawar City. User feedback was collected to verify the feasibility and applicability of the developed framework in actual projects.

With the proposed system, the sharing and exchanging of information are highly efficient, supporting communication, visualization, volume calculation, and other significant analyses for the construction project stakeholders. Besides, the developed model provided 3D visualization of geological data in B-rep and voxels format, an advantage over the traditional method supported by 2D representation. The proposed voxel model is flexible enough to adjust the size at a different scale to assimilate the inhomogeneous geological condition data. Moreover, the geological information in BIM and GIS were represented in the IFC and CityGML, which supports easy and efficient information exchange among stakeholders. The calculation of the volume of a specific geological layer available in the underground space and the determination of a safe construction zone made the system effective in decision-making. These functions determine a suitable location or route for an infrastructure project that is verified by industry users.

The study has been applied considering only two types of soil layer and rock layer. The two types of geology are considered because of the available resources. For example, in the case study implementation, the geology type is mainly soil and rock, which is suitable for the demonstration of the proposed method. The geological modeling in the context of this proposal depends on the site investigation and exploratory data. For constructing complex geological model, three steps procedure can be followed. Specifically, voxels are used to model the complex geological features. The size of voxel can be selected according to the user demand. For homogenous and simple geology, bigger voxels can be selected, while for complex geological features, smaller voxel size can be used to accurately model and depict the as-built condition. The voxel size is the main trigger that can be utilized to efficiently represent the complex variation in the geology. Our proposed voxel-based method is efficient and flexible enough to model the complex geological features and act as base for underground digital twin. Moreover, we are collecting additional data of sites having complex geological condition in our future studies for further demonstration of the proposed method. For instance, the study creates voxel-based using B-rep model as a foundation. Although, the proposed algorithm takes several measure to avoid the information loss; however, an alternate procedure can be adopted in the future study to transform a geological model directly into a voxel-based model or start with the voxels from the initial step.

CRediT authorship contribution statement

Muhammad Shoaib Khan: Data curation, Software, Visualization, Writing – original draft. **In Sup Kim:** Investigation, Software, Validation, Writing – review & editing. **Jongwon Seo:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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