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BIM-Based Tunnel Information Modeling Framework for Visualization, Management, and Simulation of Drill-and-Blast Tunneling Projects

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Abstract: Tunnel construction fundamentally differs from building and aboveground civil infrastructure projects. Drill-and-blast is one of the most common and flexible tunnel construction methods. However, it is complex and challenging because a large amount of data is generated from dispersed, independent, and heterogeneous sources. The tunneling industry still uses traditional project management techniques to manage complex interactions between these data sources that are hardly linked, and independent decisions are often made without considering all the relevant aspects. In this context, tunnel construction exhibits uncertainties and risks due to unforeseen circumstances, intricate design, and ineffective information management. Building information modeling (BIM) in the construction industry provides a solution to such issues with effective data information modeling. Existing research has considered a very general BIM semantic model and focused only a small portion of the entire drill-and-blast construction process. Tunnel boring machine (TBM) projects have successfully applied linked data models and multimodel concepts in BIM, but those technologies have yet to be adopted in drill-and-blast tunneling. To address that gap, a novel BIM-based multimodel tunnel information modeling (TIM) framework is presented here to improve project management, construction, and delivery by integrating five interlinked data models and project performance data for drill-and-blast tunnel construction. Data models of tunnel construction processes are linked to propose the Industry Foundation Classes (IFC)-Tunnel classes based on the objects, relationships, and property set definitions of the IFC schema. To validate the proposed framework, an implementation case study of a hydropower tunneling project is presented. The results indicate that the framework facilitates data sharing, information integration, data accessibility, design optimization, project communication, efficient project management, and visualization of tunnel design and construction processes. **DOI: 10.1061/(ASCE)CP.1943-5487.0000955.** *© 2020 American Society of Civil Engineers.*

Author keywords: Building information modeling (BIM); Tunnel information modeling; Drill-and-blast tunneling; Multimodeling; Industry foundation class; Linked data; Collaborative management.

Introduction

In the second half of the twentieth century, tunneling revolutionized the construction industry. It has become an integral part of transportation, energy, water supply, storage, urban utility, military facility, dam, and flood control projects. There are several tunnel construction methods, of which drill-and-blast remains one of the most popular and frequently used. It has been successfully implemented for more than a century. The drill-and-blast method is the most flexible tunnel excavation method, allowing tunneling in variable ground conditions, the excavation of any tunnel size and shape, and changes in tunnel design during construction. Furthermore, it can be used in conjunction with other tunnel excavation methods. In long, deep tunnels, a drill-and-blast hybrid with a tunnel boring machine (TBM) provides an optimal and cost-effective solution (Barton 2012).

Drill-and-blast tunneling is a cyclic construction process that generates a large amount of data consisting of borehole drill logs, geographic survey sheets, geological maps, seismic logs, discontinuity data stereographic projections, topographic survey and control points, scheduling data, items cost, rock quality designation, rock mass classification value, field test records, quality assurance/quality control (QA/QC) data, blast vibration seismograms, tunnel survey points, and site management data. The data are generated during the site investigation, design, and construction process for the project and belong to various professional fields and companies; thus, the information that needs to be shared among the stakeholders differs in type, format, scale, and availability during the project. Using all that information to plan and manage tunnel construction is a critical factor for a successful tunnel project. However, in this era of data information modeling and management technology, data exchange in drill-and-blast tunneling projects is still often performed manually using traditional project management and data exchange techniques, making it a high-risk industry. Substantial cost overruns and delays due to inefficient use of available data and coordination among stakeholders are significant issues in drill-and-blast projects. Using, analyzing, and practically implementing the diverse data produced in such projects requires a consistent and integrated management platform.

One such platform that is continuously developing is building information modeling (BIM), which integrates, digitizes, manages, and covers almost all the information required for construction

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throughout the project lifecycle (Ciribini et al. 2016; Li et al. 2014; Cerovsek 2011). BIM is not a technology but a process that has gradually transformed the architecture, engineering, and construction (AEC) industry (Howard and Björk 2008; Bradley et al. 2016). In construction projects, BIM was first introduced in the building industry, and it has shown extensive penetration, offering high productivity, budget control, better communication, better customer service, and greater efficiency (Azhar 2011). BIM is well established in the building industry, and its applications include visualization, 3D drawings, cost estimation, construction sequencing, design review, collision detection, facility management, and building code integration. In civil infrastructure projects such as bridges, roads, railways, tunnels, airports, dams, and ports, the adoption of BIM is in the early stages and is generally called civil information modeling (Cheng et al. 2016). Industry Foundation Classes (IFC) provides a BIM data exchange standard with a comprehensive digital geometric and semantic description of the built asset industry (Venugopal et al. 2012). Like BIM, the IFC standards were also mostly focused on the building industry. However, with the increase in the demand for BIM in infrastructure facilities projects, several new IFC standards need to be developed. BuildingSMART International introduced an infrastructure room in 2013, called the Infra Room, to define the standard process and information exchange requirements for BIM of infrastructure facilities (Borrmann et al. 2019). BuildingSMART international has yet to define the IFC schema for tunnel projects.

BIM technology has a lot of potential for application in the tunneling industry. However, the direct application of BIM to tunnel construction projects is not possible because the process and engineering standards of building and tunneling are entirely different. Recent research has shown how BIM could be adopted in the tunneling industry and called it tunnel information modeling (TIM). To address the complexity and diverse data in the tunnel construction process, an integrated TIM framework based on BIM has been developed for mechanized tunneling projects (Hegemann et al. 2013; Koch et al. 2017; Ninić et al. 2017). However, few efforts have been made to assist the management of activities and information sharing during a drill-and-blast tunneling project cycle. The existing literature shows that the researchers have focused on semantic models that cover only a small part of the whole project, e.g., the rock support system, while ignoring geology, ground conditions, and scheduling, which also need to be integrated. The linked data approach provides a working principle for facilitating meaningful data sharing in multidomain environments. This is a comprehensive process that requires implementation of sequential tasks to ensure effective linking between multidomain data sets. In BIM, the linked data approach for product information can be more efficiently managed by cross-linking the object-oriented data to achieve semantic interoperability (Farghaly et al. 2019). The linked data approach has yet to be adopted in drill-and-blast tunneling to consider the planning, design, and construction phases of the project. A distributed multi-model-based information management system could be used for any construction project in which distributed information needs to be integrated from different project phases, domains, and organizations (Ninić et al. 2019; Scherer and Schapke 2011).

This paper presents the development and implementation of a novel, integrated BIM-based TIM framework that uses a multimodel information management system for drill-and-blast tunneling projects. The proposed framework formalizes a drill-and-blast tunnel information model using data developed from different sources during the planning, design, and construction phases. The tunnel construction data models are built on IFC standards, and five levels of development (LODs) are defined to accommodate the drill-and-blast tunneling process. This study also proposes the IFC schema for all the elements of the drill-and-blast tunnel project that are currently not defined by buildingSMART International. To validate the proposed TIM framework, an implementation case study is presented using real data of the drill-and-blast tunneling project.

Theoretical Background

BIM

BIM is an information management technique used to design, integrate, manage, and visualize the construction process throughout the lifecycle of a construction project. It develops flexibility in the design, construction, and maintenance phases, enhancing the overall efficiency of the project (Minagawa and Kusayanagi 2015). BIM has four key elements—collaboration, representation, process, and lifecycle—which all interact to create an efficient project environment (Bradley et al. 2016). BIM is growing in the AEC industry, and works with different sorts of tools and platforms. BIM provides a semantically rich three-dimensional (3D) representation of the construction project. Also, it can incorporate design/construction drawings, construction methods, construction sequences, costs, and process documents to provide information in the form of 3D, 4D, and 5D models on a single platform (Chau et al. 2004; Goedert and Meadati 2008; Tanyer and Aouad 2005). IFC is an open-data model with a standardized digital description of the built asset facility, allowing vendor-neutral exchange of BIM models (Lai et al. 2019; Lai and Deng 2018). BIM is transforming AEC-related industries by enhancing efficiency and increasing the return on investment from projects (Reizgevičius et al. 2018). A new approach to BIM that integrates structural information, providing a time-dependent structural analysis, clash detection, structural safety, scheduling, resource costs, and site conflicts, has been introduced in recent years (Khan et al. 2019; Zhang and Hu 2011). 4D graphics for construction planning and site utilization (4D-GCPSU) is an integrated system based on an integrated project information system shown to increase the efficiency of construction projects (Hu and Zhang 2011). Some industries have specified BIM to meet the needs specific to their fields, such as civil/construction information modeling (CIM), bridge information modeling (BrIM), road information modeling (RIM), and TIM.

CIM is the general umbrella term for the application of BIM in roads, railways, airports, bridges, tunnels, and other such infrastructure. It is also known as horizontal BIM or heavy BIM because of its application to earthwork projects. Structural element, modeling methodology, and construction alignment differentiate CIM from BIM, though both use the same information exchange and management working principles (Lu et al. 2016).

The *level of detail* concept was initially introduced in computer graphic models for efficient visualization; 3D objects far away from the user's viewpoint have few details, whereas near objects are shown with more details (Luebke et al. 2002). In computer graphics, the level of detail is used to reduce the computational complexity and improve the efficiency of geometrical graphics. Such approaches aim to model objects according to a specific method of analysis with the most appropriate geometry and representation. This enables both analysis and visualization of the same object with various degrees of resolution and representation at each level of detail (Gröger and Plümer 2012). In contrast, the LOD concept in BIM considers both geometrical and semantic information (Cheng et al. 2016). Considering that the level of detail is no longer used in the BIM context and to avoid confusion in this paper, LOD refers to

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level of development. There are several proposed definitions of LOD in the context of BIM, but the basic principle of LOD in BIM is to specify the minimum required information that a model must contain at different phases of the project (American Institute of Architects 2013; BIM Forum 2019; Building and Construction Authority 2012). LOD varies depending on the requirements of the stakeholders, which are comprised of different amounts of information for the building components (Latiffi et al. 2015; van Berlo and Bomhof 2014; Xing et al. 2010; Xu et al. 2019). Given that the information and simulation details required at different stages of the project determine the LODs, a higher LOD leads to more detailed information, e.g., the construction phase has a higher LOD than the preconstruction phase (Boton et al. 2015). LODs mostly focus on building elements to standardize BIM in the building industry. There is no comprehensive definition of LOD for civil infrastructure projects that differs from that used in building projects (Cheng et al. 2016). The LODs need to be defined for the drill-and-blast tunneling project to ensure the minimum amount of relevant geometric and nongeometric information required to execute each phase of the project; any information beyond this minimum level is considered wasteful. This minimum information is necessary for engineers and project managers for decision-making during each phase of the project.

Tunnel Engineering and Information Modeling

Urbanization in cities, transport mobility issues, lack of space, and constraints for surface construction all drive the need to use underground spaces. Tunneling provides an efficient, optimal, and sustainable way to use available aboveground and underground spaces. Efficient tunnel construction requires multidisciplinary knowledge and data sharing from different domains of civil engineering (Tatiya 2005a). The tunnel construction method varies from project to project because it depends on the size, shape, utility, budget, resources, geotechnical conditions, and duration of the project. The tunnel construction process becomes more complicated in unfavorable geological conditions (Hoek 2001). However, the basic principle of tunnel construction remains the same, i.e., rock mass fragmentation, mucking, and tunnel support. TBM and drill-and-blast are the most common and widely used tunnel construction methods.

A TBM is a mechanized tunneling method suitable for circular tunnels. It has revolutionized the tunneling industry with its high productivity, minimum ground vibrations, zero hazardous gas emissions, and safe working environment (Tatiya 2005b). TBM is like a moving factory with a rotating cutting that is a head pushed by a thrust system excavating the material, followed by a conveyor belt for mucking, and a tunnel support system. Drill-and-blast is a conventional tunneling method, allowing the flexibility to change the size, shape, rock support, excavation round length, and other such parameters according to the encountered geotechnical conditions (Singh and Goel 2006). The drill-and-blast method compared to TBM implements a variety of tunnel support measures to cope with varying or heterogeneous geotechnical conditions, where mixed ground or frequent alternations of weak and strong ground occur, or when large weakness zones are present (Tatiya 2005a). TBMs have a higher advance rate but also a far greater impact on the project cost and schedule, especially in the case of unexpected changes of the geotechnical conditions. Drill-and-blast is more cost efficient compared to TBMs for tunnel projects 3 km in length or less. Additionally, TBMs are not suitable for underground structures with a noncircular cross section such as large underground powerhouse caverns, or for any tunnel with an inclination of more than 6°; however, drill-and-blast can work well under such geometrical requirements. In addition, the drill-and-blast method utilizes quick mobilization using standard equipment for the required excavation operations. On the other hand, mechanized tunneling requires considerable investment as well as careful decision-making and planning to design and deploy a TBM for project-specific geotechnical conditions (Girmscheid and Schexnayder 2002). Drill-and-blast is a cyclic excavation process of rock blasting using explosives, followed by mucking with dump trucks and the installation of rock support. A detailed description of drill-and-blast operations is shown in Fig. 1.

A tunneling project generates a significant amount of information from several discrete work streams that have various data

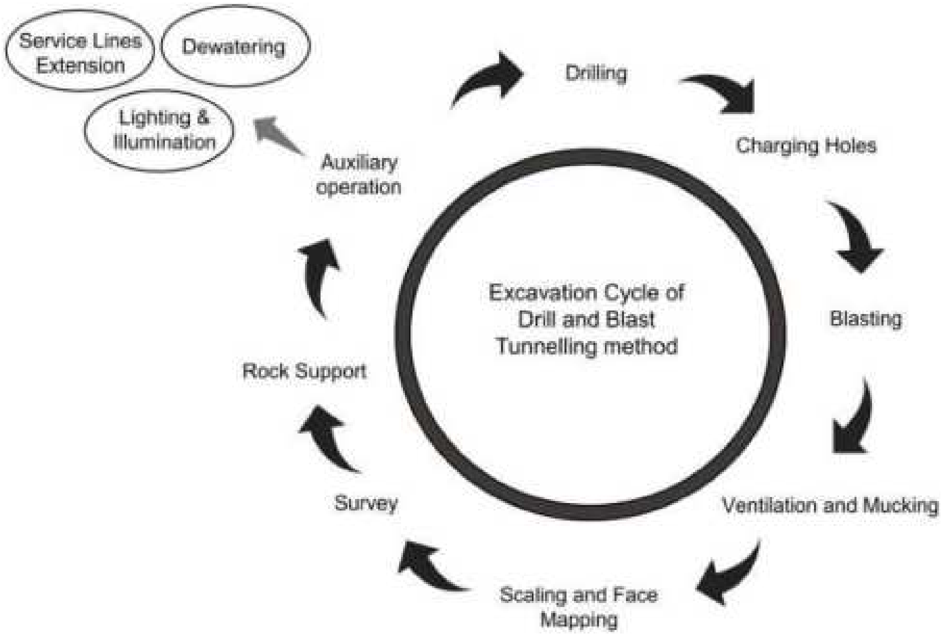

Fig. 1. Traditional excavation cycle of the drill-and-blast tunneling method.

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formats, sources, and types and are loosely coupled to each other. The data are generated based on prefeasibility of the construction stage of the tunnel, including the geotechnical data, project documents, tunnel analysis, field measurements, and project status reports. The format of the data differs widely, being handled by different project actors over the course of the project. In practice, all the data for the drill-and-blast tunneling project are stored in the form of text documents, hard copy paper form, spreadsheets, computer-aided design (CAD) drawings, diagrams, and images, and generally data exchange between the project participants is performed manually. This information is managed by different professionals using different sorts of systems for specific applications. All this information is highly interdependent and needs to be integrated, but no single system can integrate it because of the different formats. BIM can provide an integrated and collaborative platform for complex projects such as tunneling. Parametric modeling generates intelligent objects based on the characteristics and interaction among components with real-world behavior (Tanoli et al. 2018). The concept of BIM in the tunnel industry is generally named TIM and contains a 3D representation of the tunnel and its components, integrating all the information and processes of excavation. Table 1 summarizes the academic papers of BIM in the tunneling industry. IFC technology provides interoperability and standardization of information throughout the industry (Froese 2003; Ramaji et al. 2020). Thus, to address the interoperability issue for monitoring and predicting time-dependent settlements in a metro tunneling project, BIM was linked with a numerical simulation in the IFC environment (Koch et al. 2017). For instance, the influences of tunnel-induced settlements on the outer surrounding boundary, lining shell, and lining segment are modeled at three different LODs based on the element's geometry and semantic information, which depends on the objective of analysis (Ninić et al. 2017).

Another example was a BIM-three dimensional geographic information systems (3DGIS) platform to integrate the geographic and geometric information for the facility management of utility tunnels by providing visual monitoring and continuously updated information in a real-time project (Lee et al. 2018). BIM can be effectively used for operation and maintenance (O&M) of utility tunnels by integrating it with an O&M database and monitoring system (Yin et al. 2020). An integrated 3D BIM-geological platform to visualize soft ground settlements and the risk associated with nearby buildings in urban area tunneling has also been developed (Providakis et al. 2019). An integrated information model [Simulations for multilevel Analysis of interactions of Tunneling based on BIM (SATBIM)] has been presented for the structural analysis and visualization of a mechanized tunneling project, in which the structural elements of the tunnel are modeled at different LODs using realistic geometric and nongeometric information (Ninić et al. 2019). An integrated 3D geological model of conventional tunneling was developed to visualize geological information observed during the construction of the Mikusa Tunnel in Japan (Sawamura et al. 2014). Implementation of BIM in the Brenner Base tunnel project has increased productivity, design optimization, and data sharing and helped in the decision-making process (Sorge et al. 2019). A holistic library, which is an integral part of BIM, was developed for the design stage in Autodesk Revit and implemented in two New Austrian tunneling method (NATM) projects (Cho et al. 2012).

Problem Statement and Objective

Due to the distinctive nature of the drill-and-blast design and construction process, information about the geology of the project area, rock support system, concrete lining structure, scheduling, and cost as well as as-built information needs to be integrated and complemented with a tunnel technical analysis. Table 1 shows that existing research about TIM considers (1) BIM semantic models that focus only a specific portion of a drill-and-blast tunneling project and neglect the integration of the entire construction process, i.e., focus solely on either rock support models, or tunnel lining, or geological rock models; (2) the concept of a multimodel container, which has been applied to mechanized tunneling projects, yet needs to be adapted for conventional drill-and-blast tunneling projects; (3) practical implementation of BIM in tunneling that is limited to a few industry cases; and (4) construction process simulation, which is a vital visualization tool in BIM but has not been studied in drill-and-blast tunneling. Considering that research gap and the reluctance to adopt BIM in drill-and-blast tunnel construction, this research intends to develop and verify a TIM framework for efficient tunnel project management. It uses and links all the data relevant to a drill-and-blast tunneling project from design to construction phase. Furthermore, a tunnel technical analysis is linked with the design and construction process to provide a platform to support decision-making, assessment, and management of the construction process. Lastly, five LODs are defined to enable right deliverable information of the drill-and-blast tunnel construction process: the feasibility, preliminary design, detailed design, construction, and commissioning phases.

Methodology

TIM Concept

Drill-and-blast tunneling projects generate a large amount of data from diverse construction engineering disciplines. The integration of this data is necessary throughout the construction process. It contains loosely coupled, incompatible, and scattered information that is nonetheless profoundly interdependent in the form of design drawings, site information, schedules, progress, monitoring, and tunnel stability analysis (Fig. 2).

The building industry effectively uses advanced data management and information modeling techniques; however, drill-and-blast tunneling still implements traditional project management techniques. The data is stored and managed in text documents, spreadsheets, 2D drawings, photographs, and images that are very difficult to interpret and integrate without modern information modeling techniques. Furthermore, all that information is inconsistent and unlinked with the drill-and-blast tunneling construction process that provide comprehensive project information to stakeholders at any point in the project lifetime. Typical 2D CAD drawings contain all the design information for the tunneling project. CAD drawings are not a good communication platform for the construction of complex infrastructure projects (Marzouk and Abdel Aty 2012). In drill-and-blast tunneling, it is of great importance to use advanced integrated data management and information modeling techniques so that all the data generated from the design phase to the construction phase can be fully and efficiently used. Over the years, several 2D and 3D finite element geomechanics modeling techniques have been available, but they cover only geomechanical behavior of the tunneling process, such as stress distribution, the stability of excavation, and deformation. Data information modeling and integrated data management are needed to link all the information generated during the entire period of a drill-and-blast tunneling project.

The proposed TIM interaction platform provides a multimodel for drill-and-blast tunneling projects. It includes tunnel construction sequence, construction method, construction elements,

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Table 1. Characteristics of existing tunnel BIM literature

Article type	Authors/year	Tunnel shape/type	Excavation method	BIM	BIM tools	Implementation	Implementation project
Conference	Yabuki (2008)	Circular	Shield TBM	3D model	CAD, IFC-based 3D BIM	No	No
Journal	Lee and Kim (2011)	Mouth profile/road tunnel	Not mentioned	3D model	CAD, IFC-based 3D BIM	No	No
Conference	Borrmann et al. (2012)	Mouth profile/transportation	Not mentioned	3D model	CAD, Autodesk Inventor, XML version 1.1	No	No
Conference	Hegemann et al. (2012)	Circular	EPB, TBM	3D model	SolidWorks and OpenIFC	Theoretical	Ruhr-UniversitätBochum
Conference	Cho et al. (2012)	Circular/transportation	NATM	3D model	Revit and Digital Project	Theoretical	Samtan 1 tunnel
Conference	Yabuki et al. (2013)	Circular	Shield TBM	3D model	Civil3D, Revit Structure version 2011, Google SketchUp	Theoretical	Central Beltway Shinagawa line in Tokyo, Japan
Conference	Borrmann et al. (2013)	Circular	Shield TBM	3D model	CAD, UML, IFC 4	No	No
Conference	Amann et al. (2013)	Circular	Shield TBM	—	UML, IFC	No	No
Conference	Min and Zhewen (2014)	Not mentioned	Not mentioned	Ontology-driven BIM	IFC	Theoretical	Hongmei South Road Tunnel, Project Shanghai Huangpu
Conference	Heikkilä et al. (2014)	Transportation	NATM	3D model	2D drawing, 3D laser scanning	Theoretical	Five different tunnel designs
Journal	Jubierre and Borrmann (2015)	Circular/railway	TBM	3D model	CAD, .NET Framework	Theoretical	Second main suburban track, Munich
Journal	Borrmann et al. (2015)	Circular	Shield TBM	3D model	CAD, UML, IFC	Theoretical	No
Conference	Sami et al. (2016)	Circular	Shield TBM	3D model	Revit	No	No
Journal	Daller et al. (2016)	Noncircular/transportation	Does not consider	3D model	CAD	Theoretical	Karavanke tunnel, Granitztal tunnel chain
Journal	Lee et al. (2016)	Noncircular/transportation	NATM	3D model	IFC 2 × 3 in CAD-based environment of NATM	Theoretical	Namhu tunnel Andong, South Korea
Journal	Koch et al. (2017)	Circular/subway	TBM	3D BIM and FE model	IFC/open BIM/FEM	Practical	Wehrhahn-Linie (WHL) subway tunnel construction
Journal	Zhou et al. (2017)	Circular/transportation	Not mentioned	3D BIM and 4D simulation	Civil 3D, CATIA software, Inventor, Google Earth	Theoretical	Shigu Mountain and Xingu Mountain tunnel
Conference	Osello et al. (2017)	Noncircular	Not mentioned	4D and FEM	Revit, AutoCAD, RS3	Numerical analysis	Paniga tunnel
Journal	Ninić et al. (2017)	Circular	Shield TBM	3D BIM with AI design	SATBIM, Revit, Dynamo, GiD, KRATOS	Theoretical	Numerical simulations
Journal	Lee et al. (2018)	Utility tunnels	Not mentioned	BIM-3DGIS	C# Language, IFC, CityGML	Illustrative	Not mentioned
Conference	Beaufils et al. (2019)	Not mentioned	Not mentioned	No	GeoSciML and Information Delivery Manuals (IDM)	No	No
Journal	Ninić et al. (2019)	Circular	TBM	3D BIM tunnel with numerical modeling	SATBIM, Revit, Dynamo, Kratos	Numerical analysis	Numerical simulations
Journal	Providakis et al. (2019)	Circular tunnel	Not mentioned	3D BIM	Revit, ArchiCAD, MATLAB	Theoretical	Numerical simulations
Journal	Chen et al. (2020)	Tunnel facilities	Not mentioned	3D BIM with integrated e-documents archives	CAD, Prototype System Interfaces for FM	Prototype	Lingxia tunnel
Journal	Yin et al. (2020)	Utility tunnels	Not mentioned	3D BIM	AutoCAD version 2016, Revit version 2016, ARCHICAD version 21	Prototype	No

Note: EPM = earth pressure balance; FEM = finite element method; FE = finite element; and FM = facility management.

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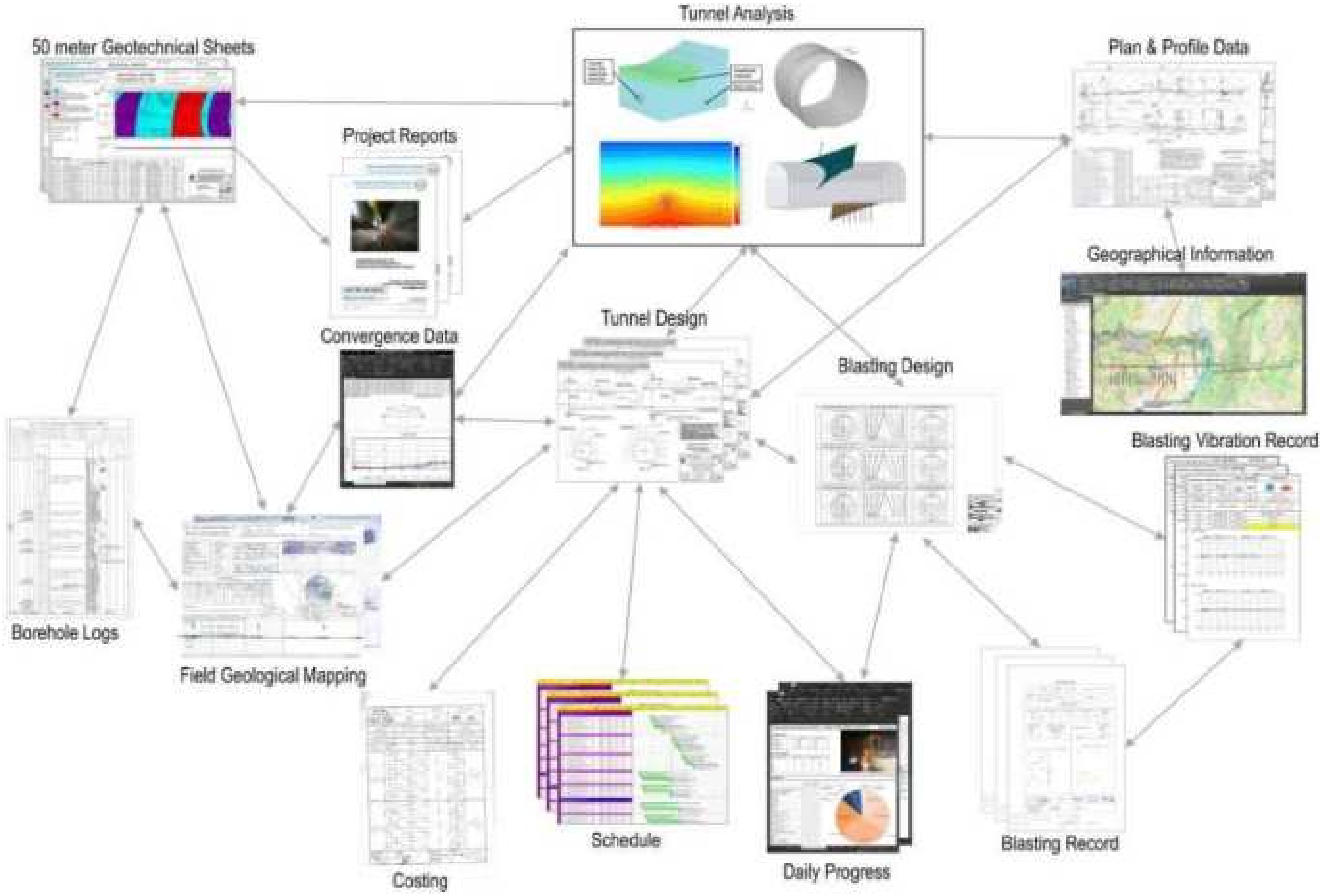

Fig. 2. Traditional drill-and-blast tunneling project information stored in the form of text documents, spreadsheets, 2D CAD drawings, 2D and 3D simulation models, and images and diagrams, along with the interrelationships among them.

materials, equipment, and actors, which are the essential components required to design a TIM model, and it supports different aspects of the project. As shown in Fig. 3, the TIM system architecture consist of a data source layer containing all the project data sources, a multimodeler encompassing holistic and object-oriented models, an analysis layer that computes and analyzes data, an integration layer that provides a unified data interface, and an application layer that implements TIM in the tunneling process. The TIM thus collects all the information produced in different domains of the project, allows participants to contribute dynamically, builds a simulated environment, provides consistent information, helps in critical decision-making, and manages policies at every phase of a tunneling project (Fig. 4). The drill-and-blast is the cyclic process, and tunnel construction activities mostly remain the same for every project (Hoek 2007; Spathis and Gupta 2012). The proposed TIM is based on the scientific knowledge of the drill-and-blast tunneling construction process (Bickel et al. 1996). It considers all the major activities and components of drill-and-blast tunneling that are necessary and performed in the same sequence for all the projects (Brox 2017). Therefore, the proposed framework is generalizable for all tunneling projects using the drill-and-blast method.

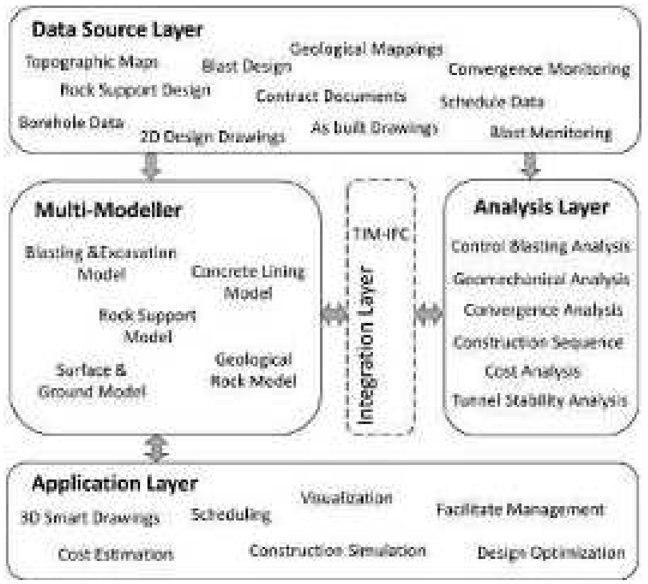

Fig. 3. Architecture overview of a TIM framework for drill-and-blast tunneling.

Data Source Layer

A drill-and-blast tunneling project generates a large amount of data from diverse sources in different file types and formats during the concept, design, construction, and operation phases of the project (Fig. 2). At the feasibility stage, site investigation and testing data are collected from aerial photographs, survey sheets, and geophysical surveys using electric resistivity and seismic refraction techniques, borehole drilling and logging, in situ and laboratory testing, and geological surveys. The type and format of the data differ, including images, spreadsheets, and text documents. At the

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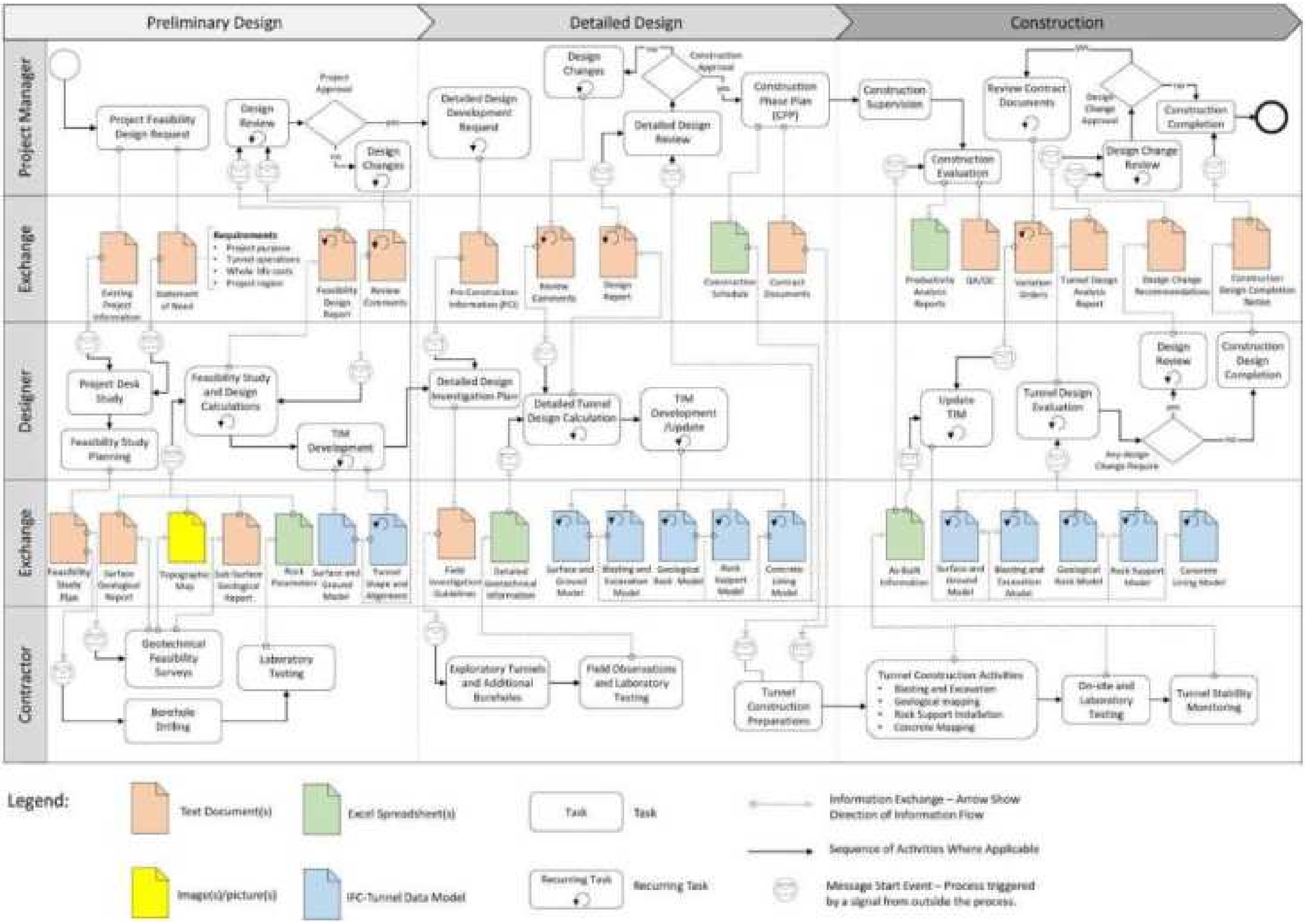

Fig. 4. Business process model and notation (BPMN) diagram showing process map and information flow of TIM based on IDM.

design stage, data are acquired from additional borehole drilling and logging, exploratory tunnels, laboratory testing, feasibility reports, project documents, and tunneling standards. This provides a guideline to develop detailed tunnel design in the form of CAD drawings. At the construction stage, field data such as geological mapping, face coring and logging, blasting logs, field testing, measuring while drilling, convergence monitoring, ground vibration monitoring, cost, progress evaluation, and as-built information logs are recorded and stored in the form of images and spreadsheets. These data are utilized by designers and project managers to perform detailed tunnel analysis stored as images and text documents, vibration monitoring analysis stored as spread sheets, tunnel excavation and support evaluation analysis stored as spreadsheets and images, and long wall geological mapping stored as CAD drawings.

Multimodeler

Intelligent 3D object-oriented tunnel information models link all the information gathered through the data source layer. This layer is based on the multimodel information systems already used for construction projects (Scherer and Schapke 2011). These models contain tunnel components from different disciplines. The multimodeler includes not only geometric data found in 3D CAD models but also nongeometric data containing a variety of information about different tunnel elements, which adds an extra dimension to the project models. Intelligent models consist of intelligent objects that not only show a 3D visualization of the objects, but also accommodate the model behavior of interdependent objects. Such models contain attributes and spatial information, automate decisions and design checks/changes, uphold design consistency, can integrate with project activities, update information dynamically, and handle facility management aspects (Halfawy and Froese 2005). If there are any changes to the geometric or nongeometric information, the model updates all the information related to the objects in the model automatically. The TIM multimodeler contains five intelligent models to accommodate the drill-and-blast tunneling process. These models are built using IFC standards to provide interoperability, data standardization, and integration among participants. Extension of existing IFC structure based on the spatial and element classes provides a solution for modeling drill-and-blast components.

The EXPRESS-G diagram provides a visual representation of the overall IFC-based data models for drill-and-blast tunnel construction (Fig. 5). An EXPRESS-G diagram consists of an IFC data model element of the major elements (A,B,C, . . . ,O) shown in the Appendix I. The tunnel has not been included in the IFC standards, but in the future may include IFC-Tunnel (Building Smart 2020). According to the recent IFC4×3 schema, our proposed schema has some of the individual elements and spatial

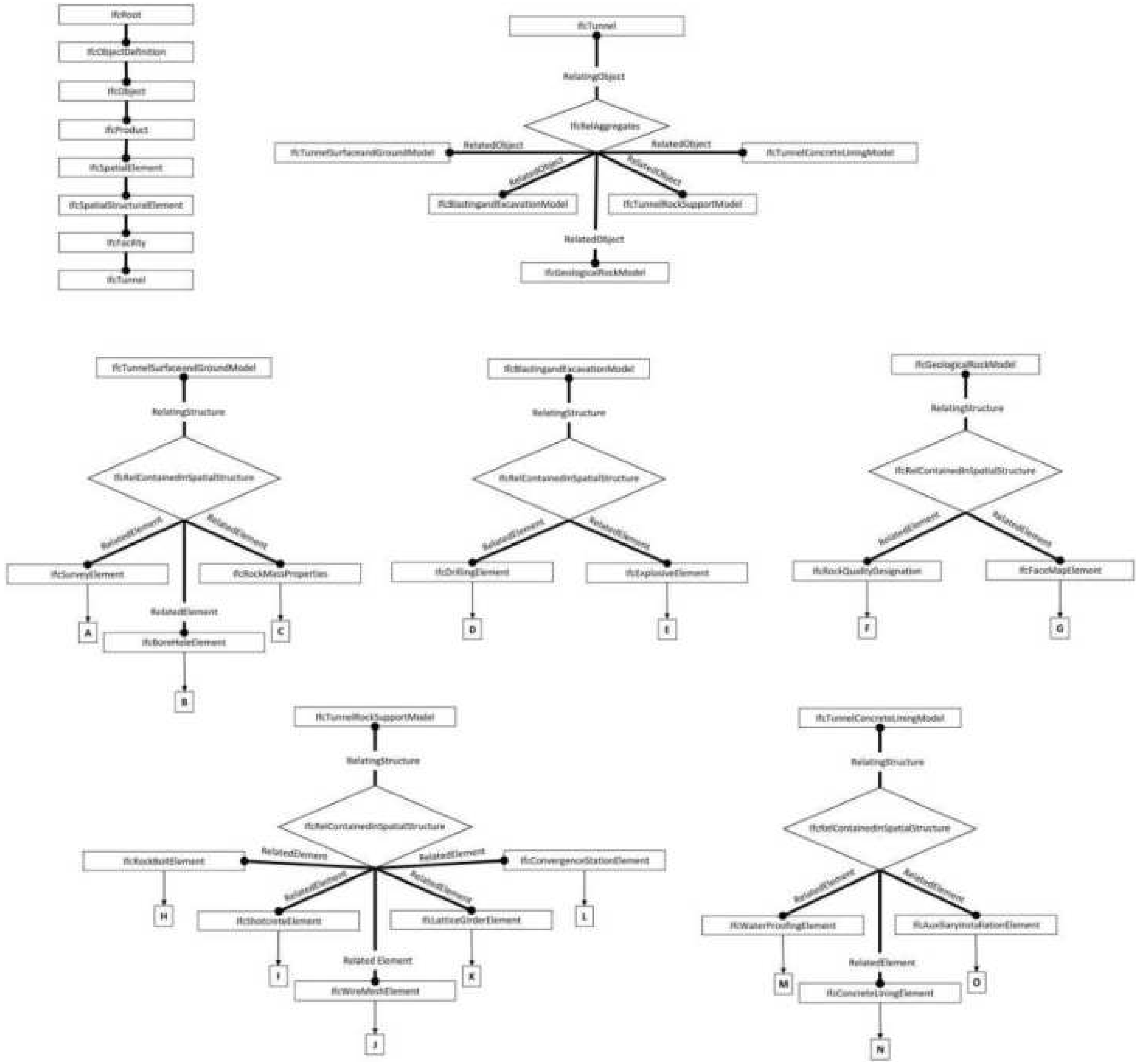

Fig. 5. EXPRESS-G diagram of an overall IFC-based data model for drill-and-blast tunnel construction method. The extract of the A,B,C, . . . ,O is shown in Appendix I.

structure elements defined in IFC4×3 such as IfcBorehole, but still lacks further details such as attributes of IfcBorehole. In this study, IFC-Tunnel is used specifically for drill-and-blast (cyclic method), and its five parts are proposed along with the specifications of the objects and structures. A tunnel represents a structure that provides the facilities needed to transport humans, machines, and water, such as a hydropower tunnel. IFC-Tunnel is used to build the primary spatial structure of the tunnel and provide hierarchical linkage between all the elements. IfcSurfaceandGroundModel, IfcBlastingandExcavationModel, IfcGeologicalRockModel, IfcRockSupportModel, and IfcConcreteLiningModel are the five parts of IFC-Tunnel. Table 2 describes all the IFC classes. A unified modeling language (UML) class model depicts all the proposed and existing classes along with their attributes (see Appendix II).

IfcSurfaceandGroundModel consists of three classes, IfcSurveyElement, IfcBoreHoleElement, and IfcRockMassProperties, which represent the topographic information, geological features, and geological properties of the rock, respectively. IfcSurveyElement represents all the topographic information and spatial data present on the ground above the tunnel. The geological information of the strata above the tunnel, such as lithology, is included in IfcBoreHoleElement, whereas the geological properties of the strata/rock and the rock quality designation are contained in IfcRockMassProperties. IfcDrillingElement and IfcExplosiveElement are derived from IfcBlastingandExcavationModel to represent the drilling and blasting processes, respectively. IfcDrillingElement represents the information of the drilling mechanism, design variables of the drill holes, and the drilling tool. IfcExplosiveElement

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Table 2. Description of the IFC classes

Serial No.	Entity	Definition
1	IfcRoot	Most abstract type to define all the entities on the subsequent layers; it has four attributes: GlobalId, owner history, name, and description
2	IfcObjectDefinition	Subtype of IfcRoot; defined as the generalization of a semantically treated object or process
3	IfcObject	Subtype of the IfcObjectDefinition and generalization of semantically treated physical objects
4	IfcProduct	Geometric or spatial representation of the object; covers the physical object (IfcElement) and the spatial Items (IfcSpatialElement)
5	IfcSpatialElement	Subtype of IfcProduct; defined as the generalization of the spatial structure or zones
6	IfcSpatialStructuralElement	Generalization of all spatial elements required to define a spatial structure
7	IfcFacility	Subtype of IfcSpatialStructureElement such as IfcBuilding or IfcRoad
8	IfcTunnel	Proposed subtype of IfcFacility; used to represents the primary spatial structure of the tunnel and provide hierarchical linkage between all the elements
9	IfcTunnelSurfaceandGroundModel	Represents topographic information, geological features, and geological properties of the rock
10	(a) IfcSurveyElement	Represents all the topographic information of entities and spatial data present on the ground above the tunnel
11	(b) IfcBoreHoleElement	Represents the geological information about the strata of the construction project
12	(c) IfcRockMassProperties	Represents the index properties of the strata/rock such as rock strength and RQD
13	IfcBlastingandExcavationModel	Represents the drilling- and explosive-related information to excavate the rock
14	(a) IfcDrillingElement	Represents the information of drilling mechanism and design variables of drill holes and drilling tool
15	(b) IfcExplosiveElement	Represents the information of index properties of the explosive, blast design, and secondary operation such as vibration monitoring
16	IfcGeologicalRockModel	Represents the geological features and rock quality index
17	(a) IfcFaceMapElement	Representation of the geological features and the condition of rock around the tunnel periphery at different stations
18	(b) IfcRockQualityDesignation	Representation of evaluation of the rock quality index and prediction of the required support
19	IfcTunnelRockSupportModel	Represents the characteristics of support elements for the stability of the tunnel
20	(a) IfcRockBoltElement	Represents the information regarding the support design of rock bolt and its types to stabilize the rock
21	(b) IfcShotcreteElement	Represents the composition, application, and required amount of shotcrete to make the surface stable
22	(c) IfcWireMeshElement	Represents the design parameters of the wire mesh
23	(d) IfcLatticeGirderElement	Represents the design parameters of the lattice girder
24	(e) IfcConvergenceStationElement	Represents the design parameters of the convergence station and measurements of the tunnel deformations
25	IfcTunnelConcreteLiningModel	Represents the waterproofing, finished surface, and necessary entities to make the tunnel operational
26	(a) IfcWaterProofingElement	Represents the entities of drainage and design measurements to control the flow of water
27	(b) IfcConcreteLiningElement	Represents the composition and mix design of the concrete and design measurements of the reinforcement bars to give the stable finished surface
28	(c) IfcAuxiliaryInstallationElement	Represents necessary entities such as lightning, power supplies to run the operation of the tunnel

Note: RQD = rock quality designation.

represents the information of the index properties of the explosive, blast design, and secondary operations, such as vibration monitoring.

IfcFaceMapElement and IfcRockQualityDesignation are derived from IfcGeologicalRockModel to describe the geological features and rock quality near the face of the tunnel. IfcFaceMapElement is a representation of the geological features and conditions of rock around the tunnel periphery at different stations. IfcRockQualityDesignation represents evaluation of the rock quality index and prediction of the required support.

IfcTunnelRockSupportModel is further classified into five classes: IfcRockBoltElement, IfcShotcreteElement, IfcWireMeshElement, IfcLatticeGirderElement, and IfcConvergenceStationElement. All these classes represent the required support elements for stability of the tunnel. IfcRockBoltElement represents information on the support design of rock bolts and the types that stabilize the rock. IfcShotcreteElement represents the composition, application and required amount of shotcrete needed to make the surface stable. IfcWireMeshElement covers the design parameters of the wire mesh. IfcLatticeGirderElement is related to the design parameters of the lattice girder. IfcConvergenceStationElement represents the design parameters of the convergence station and measurement of the tunnel deformations.

Finally, IfcTunnelConcreteLiningModel is classified into three classes: IfcWaterProofingElement, IfcConcreteLiningElement, and IfcAuxiliaryInstallationElement. IfcWaterProofingElement represents entities related to the drainage, and design measurements to control the flow of water. IfcConcreteLiningElement covers the composition and mix design of the concrete, as well as design measurements of the reinforcement bars needed to stabilize the finished surface. IfcAuxiliaryInstallationElement represents the necessary entities such as lighting and power supplies needed to operate the tunnel.

Surface and Ground Model

The surface and ground model is prepared from geographical maps and borehole geological data to provide the essential basis for the feasibility and design of the excavation process, delivering a rational understanding of the tunneling conditions, excavation method, tunnel alignment, and profile. Thus, the surface and ground model allows a better understanding of the uncertainty and risk associated with the tunneling conditions, resulting in solutions

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or changes in the preliminary design based on the actual topographical and geological data. In a typical project management plan, the information of actual ground conditions is available in the form of spreadsheets, images, and text documents. In the TIM, however, the data model contains all this information in a CAD software built upon the IFC standard, which allows to add the digital description of the actual surface and ground conditions. The spatial and element classes store all the available information. IfcSurfaceandGroundModel consists of three classes, IfcSurveyElement, IfcBoreHoleElement, and IfcRockMassProperties, which represent the topographic information, geological features, and geological properties of the rock, respectively. IfcSurveyElement represents all the topographic information related to various entities and spatial data present on the ground above the tunnel. It has several attributes providing information regarding the surrounding environment, such as the location of the tunnel entrance, waterbodies present on the surface, and fault line of the stratum. The geological information of the strata above the tunnel is included in IfcBoreHoleElement. BoreHoleDiameter and BoreHoleSpacing are examples of attributes from IfcBoreHoleElement describing the diameter and spacing of the borehole, respectively. The geological properties of the strata/rock and the rock quality designation are contained in IfcRockMassProperties. BeddingPlanes and Young'sModulus are examples of attributes from IfcRockMassProperties representing the different planes and stiffness of rock mass, respectively. The spatial classes of the surface and ground model are shown in Fig. 6(a).

Blasting and Excavation Model

Blasting is a critical factor for safe and successful tunnel excavation. Blast designs change in accordance with the variation of the mechanical properties of the encountered rock mass. Therefore, several blast designs have been developed and optimized for a single project to accommodate the rock mass conditions. The blast and excavation model contain information such as the number of blast holes, hole diameter, number of relief holes, burden, spacing, depth, explosive quantities, and delay number used in each blast.

The standard tunnel blasting technique has minimal use of geological data, and all the blasting information is stored in spreadsheets, images, and graphs that are not linked to the other normal tunnel construction operations. Based on the geological conditions, closeness to sensitive structures, and tunnel cross-sectional shape, the blast design also changes throughout the course of the project. Thus, a parametric 3D model is needed to accommodate different blast designs in the same project. The 3D digitization of blasting data and linking with other tunnel information models allows engineers to better understand the blasting operations to optimize blast design, providing cost savings,

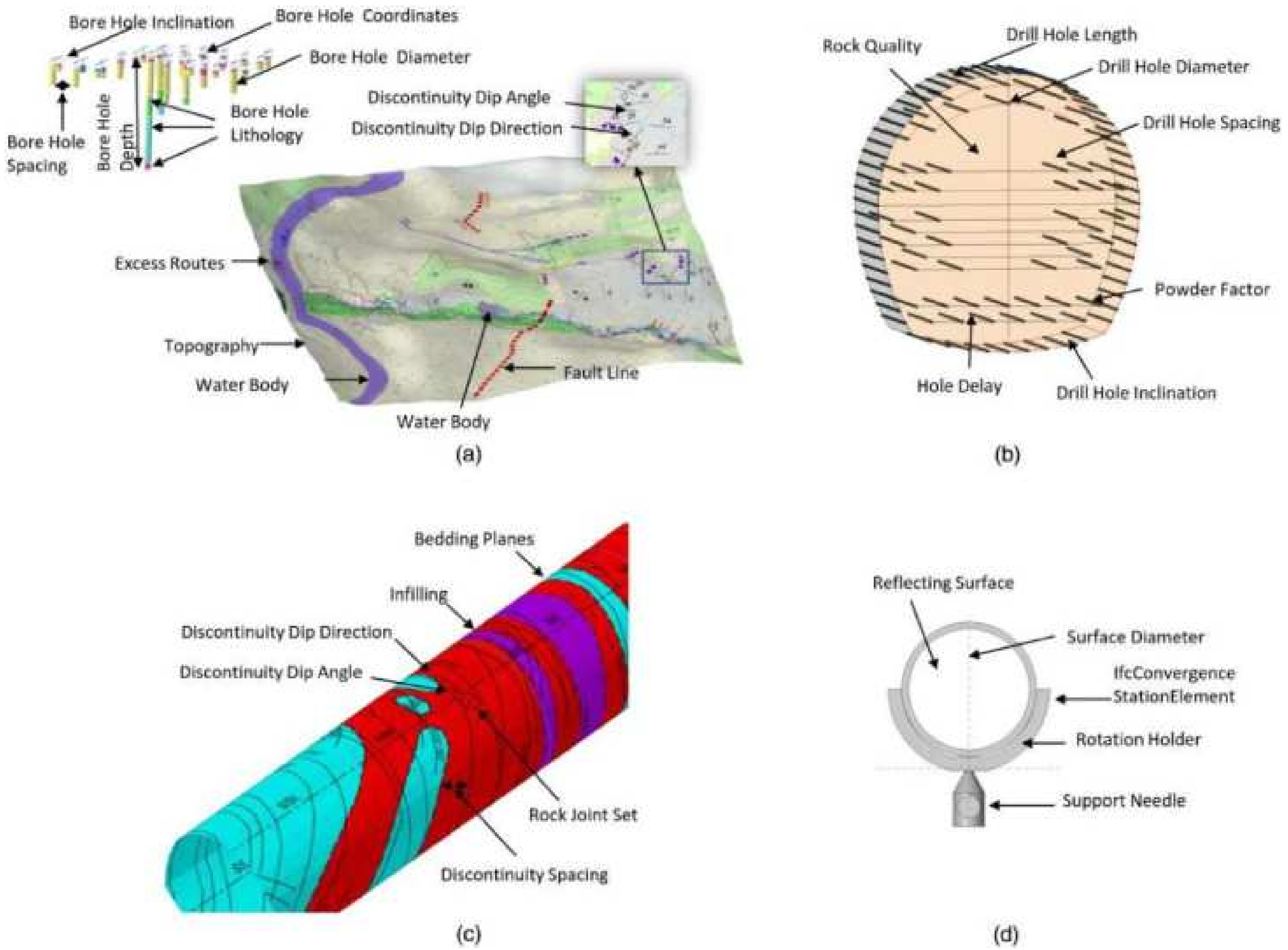

Fig. 6. TIM intelligent 3D models with extract of IFC-based drill-and-blast tunnel construction elements: (a) surface and ground model; (b) blasting and excavation model; (c) geological mapping model; and (d) convergence station model.

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operational efficiency, low ground vibrations, and safety. Three-dimensional geometric representations are also necessary for calculating the rock excavation volume. The TIM multimodeler integrates blast design information into the tunnel construction process in the blasting model, providing efficient and more detailed data analysis. The IFC schema for the excavation model is shown in Fig. 6(b) and contains the spatial elements for the drilling and blasting of rock. IfcDrillingElement and IfcExplosiveElement are derived from IfcBlastingandExcavationModel to represent the drilling and blasting processes, respectively. The first represents information related to the drilling mechanism, design variables of the drill holes, and the drilling tool. The second represents information related to the index properties of the explosive, blast design, and secondary operations such as vibration monitoring. Some examples of the attributes of IfcDrillingElement include DrillHoleLength and DrillHoleSpacing, where the first describes the drill hole length and the second describes the spacing between the drill holes according to the drill-and-blast design. PowderFactor and HoleDelay are examples of the attributes of IfcExplosiveElement, where the first explains the powder factor of the explosive needed to break the unit volume of rock and the second represents the delay during detonation of the holes in simultaneous layers.

Geological Rock Model

The geological rock model is the most vital part of a tunnel construction project. It has a significant influence throughout the lifecycle of the project. Geological mapping is conducted after the face excavation and before the installation of the rock support, documented during the tunnel construction phase, and generally stored in the form of 2D CAD drawings. The model contains information about the actual geological conditions that occurred during excavation. This information provides a guideline for the tunnel engineers designing tunnel support and lining. The geological data are beneficial to the various stakeholders of the project, from designers to construction managers throughout the design, construction, and operation phase, with the potential to reduce project risk and cost (Morin et al. 2017). The current IFC standards cannot accommodate geological information for a drill-and-blast tunnel project. Therefore, an intelligent 3D model, based on the IFC standard, was developed and linked with the TIM. IfcFaceMapElement and IfcRockQualityDesignation are derived from IfcGeologicalRockModel. IfcFaceMapElement represents the geological features and conditions of the rock around the tunnel periphery at different stations. Infilling, DiscontinuityDipDirection, and DiscontinuitySpacing are some of the attributes of IfcFaceMapElement, providing information about the filling material between two layers, the dip direction of the discontinuities, and the spacing between the discontinuities in the strata, respectively. IfcRockQualityDesignation represents evaluation of the rock quality index and prediction of the required support. Some attributes of IfcRockQualityDesignation are RQDValue, RockWeathering, and JointSetNumber, which describe the quality of the rock.

Rock Support Model

The major function of a tunnel rock support system, also known as the rock primary support system, is to keep the tunnel stable during construction. It carries the entire rock mass load after excavation, controls the tunnel deformation, and minimizes damage to the surrounding rock mass because of stress redistribution. A typical rock support system may consist of rock bolts, wire mesh, shotcrete, lattice girders, steel sets, or other stiff structural elements. The rock support system depends on the rock mass conditions. In the case of any unknown uncertainties, both schedule and cost are affected. Furthermore, because of a localized ground anomaly, such as an encountered groundwater inflow, or other construction-related divergences, there may be instances where the rock support design categories and the as-built rock support installation can vary. The rock support model incorporates all the types of rock support that are installed during the tunnel construction, providing a detailed representation of the actual conditions and assisting the various stakeholders with the analysis of the rock support system from design to construction, including the estimation of cost and schedule. The proposed TIM contains intelligent objects embedded with parametric and nonparametric IFC-based data of every rock element. IfcTunnelRockSupportModel is further classified into five classes: IfcRockBoltElement, IfcShotcreteElement, IfcWireMeshElement, IfcLatticeGirderElement, and IfcConvergenceStationElement. All these classes represent the required support elements for the stability of the tunnel (Fig. 7).

IfcRockBoltElement represents information regarding the support design of the rock bolt and its types needed to stabilize the rock. RockBoltSpacing and RockBoltLength are some attributes of IfcRockBoltElement representing the spacing between the rock bolts and length of the rock bolt according to the design calculation of support. Most BIM software supports building projects and does not have a built-in function to place the rock bolts into the tunnel geometric model; that is, tunneling rock bolts are generally installed normal to the circumference of the tunnels to increase the normal force and shear force. Thus, a visual program was developed using open-source visual programming software for the integration and placement of rock bolts normal to the tunnel geometry (Fig. 8). IfcShotcreteElement represents the composition, application, and required amount of shotcrete needed to make the surface stable. ShotcreteThickness and ShotcreteStrength are some attributes of IfcShotcreteElement, providing details about the thickness and strength of the shotcrete to meet the design specification, respectively.

IfcWireMeshElement covers the design parameters of the wire mesh. Some attributes of IfcWireMeshElement are WireMeshDiameter and WireMeshAperture, providing information on the diameter of the wire and aperture size of the mesh, respectively. IfcLatticeGirderElement is related to the design parameters of the lattice girder. LatticeGirderHeight and LatticeGirderWidth are from the attributes of IfcLatticeGirderElement, providing the height and width of the lattice girder. IfcConvergenceStationElement represents the design parameters of the convergence station and measurement of the tunnel deformations. ConvergenceStationLocation, SurfaceDiameter, and ConvergenceStationSpacing are examples of attributes of IfcConvergenceStationElement, describing the location of the convergence station, the diameter of the convergence station mirror, and the spacing between the convergence station and the tunnel, respectively. This section includes the design and characteristics of the IFC schema for the primary support elements, as shown in the Appendix I.

Concrete Lining Model

In underground structures, a concrete lining is necessary to meet the functional criteria; it provides water-tightness, protection to the primary support, durability, structural strength, hydraulic smoothness, and aesthetics (Hoek 2001, 2007). It is also known as a secondary support. Concrete lining activities are performed simultaneously with tunnel excavation to reduce the tunnel construction time. They can significantly affect the project if clashes occur or the work plan is mismanaged. The TIM provides a platform to manage, integrate, and plan the concrete lining in cooperation with other tunnel excavation activities. The tunnel lining model is built on the IFC standard by proposing a new tunnel IFC structure.

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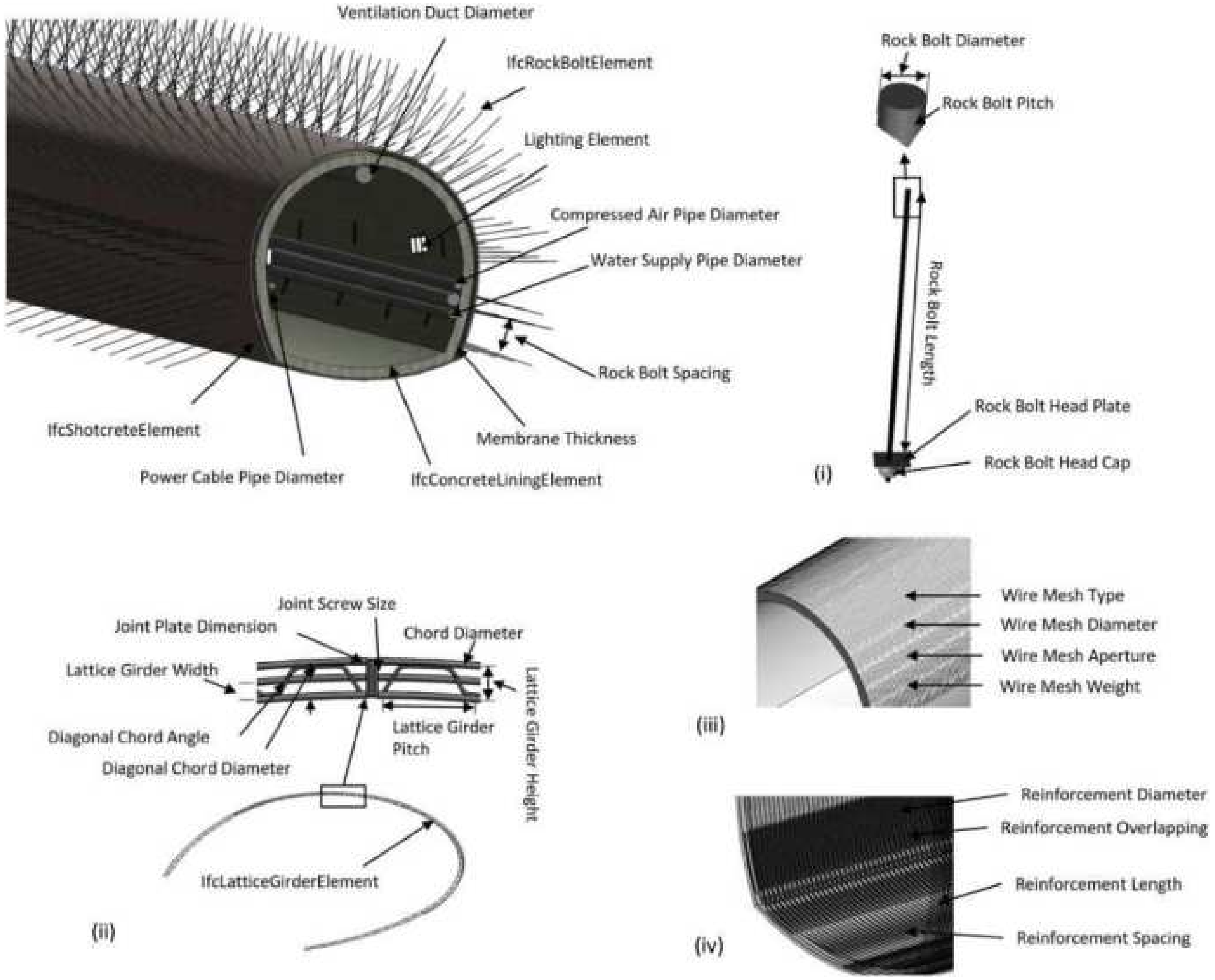

Fig. 7. TIM intelligent model of the rock support models, and its components with extract of IFC-based drill-and-blast tunnel construction elements: (a) rock bolt; (b) lattice girder; (c) wire mesh; and (d) concrete reinforcement.

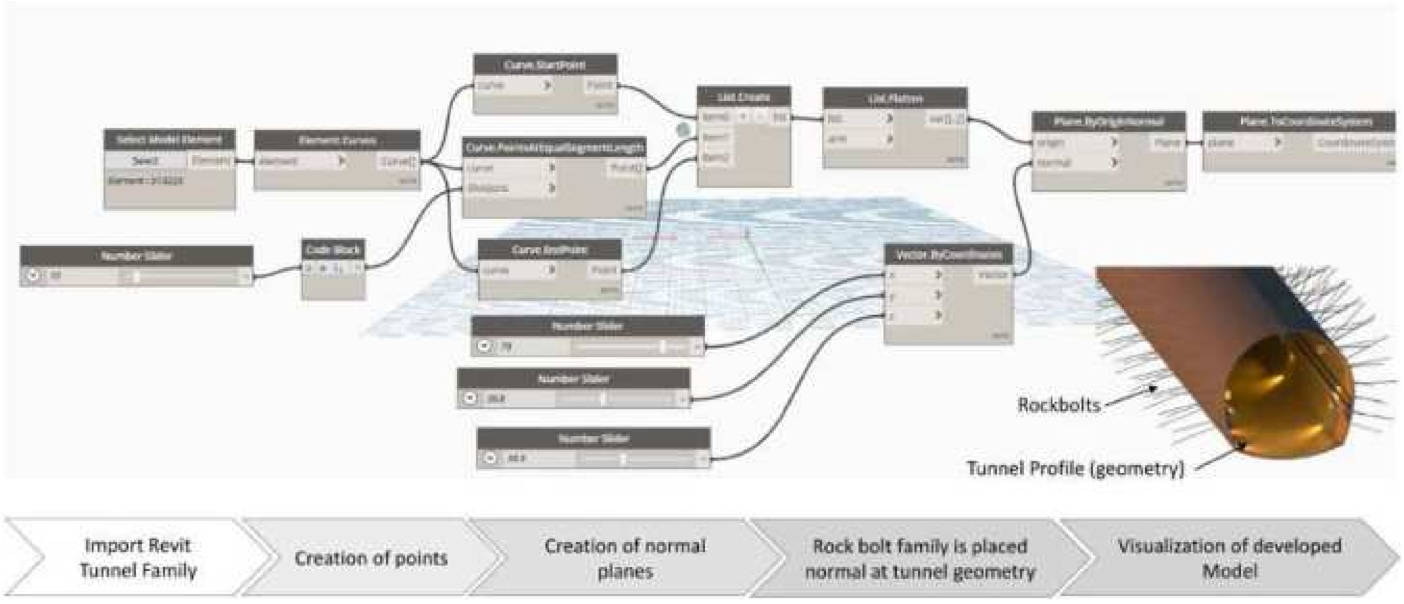

Fig. 8. Visual coding and workflow for the installation of rock bolts normal to the tunnel profile.

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The IfcTunnelConcreteLiningModel is classified into three classes: IfcWaterProofingElement, IfcConcreteLiningElement, and IfcAuxiliaryInstallationElement.

IfcWaterProofingElement represents the drainage control and design measurements to control the flow of water. MembraneThickness and DrainageHoleLength are some attributes of IfcWaterProofingElement, providing information about thickness of the waterproofing membrane to stop seepage and the drain hole length, respectively. IfcConcreteLiningElement covers the composition and mix design of the concrete, and design measurements of the reinforcement bars provide stability to the finished surface. Some examples of the attributes of IfcConcreteLiningElement include ConcreteThickness and ReinforcementYieldStrength, providing information about the thickness of the concrete lining and the reinforcement rebar strength, respectively.

IfcAuxiliaryInstallationElement represents the necessary entities such as lighting and power supplies needed to operate the tunnel. VentilationDuctDiameter and CompressedAirPipePressure are some attributes of IfcAuxiliaryInstallationElement. The first provides information about the size of the ventilation duct, while the second describes information about the compressed air pressure in the pipe needed to run the associated equipment (Fig. 7).

Integration Layer

The integration layer provides interoperability by exchanging information in TIM facilitated by the TIM-IFC classes. It defines a unique data structure based on the IFC, integrates the different layers and domain models, and describes the semantics of a drill-and-blast tunneling project. The AEC industry widely recognizes the IFC data schema as the common data exchange format for interoperability required in the information modeling of the construction industry (Eastman et al. 2008). The development of TIM-IFC is based on the National BIM Standard (NBIMS) and facilitates configuration and arrangement of information exchanges through model view definition (MVD) (Venugopal et al. 2012; Eastman et al. 2010). This layer consists of four major phases, with each having several procedural steps to integrate different data models of a large project into a single data model. Phase 1 consists of the development of a process map that describes the scope, project stages, processes sequence, and necessary information at each construction stage. The functional requirements for information exchange concerning the tunneling process for all the stakeholders throughout the project are defined and called exchange requirements. These are organized into what is called the information delivery method (IDM). Phase 1 also provides the general workflow for drill-and-blast tunneling projects following the proposed TIM framework (Fig. 4). Phase 2 structures the identified exchange requirements into a set of information packages called MVD concepts. It defines the standardized schema for data models of the drill-and-blast tunneling method to unify the data structure among all the stakeholders of the industry. The most important role of MVD is to satisfy the information requirements that need to be exchanged or transferred in the implementation schema of IFC. Fig. 11 shows the model view defining the subset information of all subdomain models for the application of TIM. The MVD for specific-use case exchange should be able to be validated by comparing it with IDM. Phase 3 involves the development of documentation guidelines and model schema for TIM-IFC. It defines the hierarchical aggregation structure for each of the classes/spatial classes and organizes them according to the relationship aggregates. Documenting the TIM-IFC object-based models helps to define the object type and the geometric information of the object, entity, attributes, and associated relationship among them to exchange data through IFC (Fig. 5). Parameters of newly created families have been defined based on the tunnel specification and IFC schema definitions. Phase 4 addresses the implementation of TIM-IFC data models. The TIM-IFC classes are defined in terms of EXPRESS-based object-oriented data models. The EXPRESS definition for TIM-IFC is provided in the Supplemental Materials. The implementation contains the IFC definition to facilitate the import/export of information data models by domain software among diverse tunneling disciplines.

This layer enables the information flow among the TIM models and between the various TIM layers. Besides, it allows different participants from the multiple domains to view and acquire the tunnel information they require at any stage of the project. BuildingSMART International has not yet defined the IFC schema for tunnels. Therefore, new generic element families and parameters were developed based on the tunnel-specific definitions. The proposed IFC schema defines all the elements that are currently not defined by the IFC schema of buildingSMART International. The integration of data models is accomplished through a TIM-IFC data model, which defines the tunnel semantics for promoting integration and data exchanges in TIM-IFC.

Analysis Layer

The analysis layer uses all the information from the data source layer and the intelligent 3D models from the multimodeler. It provides feedback and information to optimize and analyze different aspects of the tunnel construction. This layer allows the designers and construction managers to access the new information gathered during the construction phase in real time, enabling them to efficiently review the design and construction procedure. All the rock mass information collected during the course of the tunneling project is utilized to perform different rock mass characterization analyses to determine the geotechnical linear and nonlinear strength parameters of rock mass, including shear strength, principal strength, and shear-normal strength. Finite element analysis is performed to understand the behavior of rock mass based on the tunnel excavation design. Such analysis provides information about the tunnel progressive failures, rock support interactions, pore water pressure, stress, and strain. Rock support analysis estimates deformation in the tunnels of a rock support system based on the tunnel design and geotechnical parameters, including tunnel size and shape, in situ stresses, geology, rock support parameters, ground reaction curve, and support reaction curve. Stereographic projection analysis provides information about the structural geology of the project area. These data are used to perform tunnel stability analysis of rock wedges around the tunnel periphery and tunnel rock face. Convergence is one of the major risks in drill-and-blast tunnel construction due to the round length and excavation time. There is a minimum allowed convergence for every project. Time-dependent behavior of the surrounding rock mass is observed using convergence analysis to keep the convergence allowance within specified limits and safely perform tunnel activities. During construction, cost and schedule analyses are performed to keep the project budget and schedule on track. The vibration attenuation analysis from the blasting model provides the feedback to revisit the blast design to obtain permissible charge weights that keep vibration limits to safe levels. Besides, the analysis of drilling data from blasting and probing can be analyzed to predict the rock mass condition and thus the appropriate rock support ahead of the tunnel face (van Eldert et al. 2019). Analysis in integration with the

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multimodeler may provide the feedback to understand the tunnel excavation response and provide meaningful information to project managers and tunnel design and construction engineers to review the tunnel design and construction procedure and make critical decisions.

Application Layer

The application layer is the most flexible layer of the TIM and provides the output of the TIM in a drill-and-blast tunneling project. In other words, the application layer defines the various engineering applications of the TIM, such as 3D drawings, visualization, construction simulation, design optimization, clash detection, cost estimation, scheduling, and facility management. Different stakeholders from the design to the construction phase are able to see the information and analysis results they need in a compact form by providing the relevant pieces of information stored in the TIM with a particular.

LOD

TIM supports the representation of geometric and nongeometric information of a drill-and-blast tunnel construction project using five metrics in terms of different LODs to determine the minimum information required to perform tasks or support decisions at each stage of the project. The LODs for drill-and-blast tunneling define the appropriate level of geometric and nongeometric information required at each phase of the project. This ensures the minimum information at each stage of the project that is necessary without risking the project, while also avoiding too much information, which can be wasteful. During the different phases of the tunneling project, the amount of nongeometric information is growing. Based on this nongeometric information, the geometric information of the models is also increased. For example, during the preliminary design phase, geological information is collected using borehole data and seismic data, which provides the basic stratigraphic geological information of the subsurface. In the detailed design phase, the geological information is improved with the help of excavations of the pilot tunnel, laboratory testing, and more exploratory drilling; however, even this information is still not enough to provide exact geological information about the tunnel excavation path. During the construction phase, a geologist examines the rocks and tunnel faces in detail and provides detailed geotechnical information that provides precise geological information of the tunnel excavation path. Thus, such nongeometric geotechnical data at each phase of the tunnel provide more detailed information that enhances the geometric information of the geology at each phase of the project. This information is then used to update TIM. The LODs enable efficient data analysis, decision-making, and visualization of the same objects using the minimum information required at different stages of tunnel construction. Furthermore, different LODs of the same object contain diverse information that can be combined and integrated gradually. Thus, the completeness of a tunnel model increases

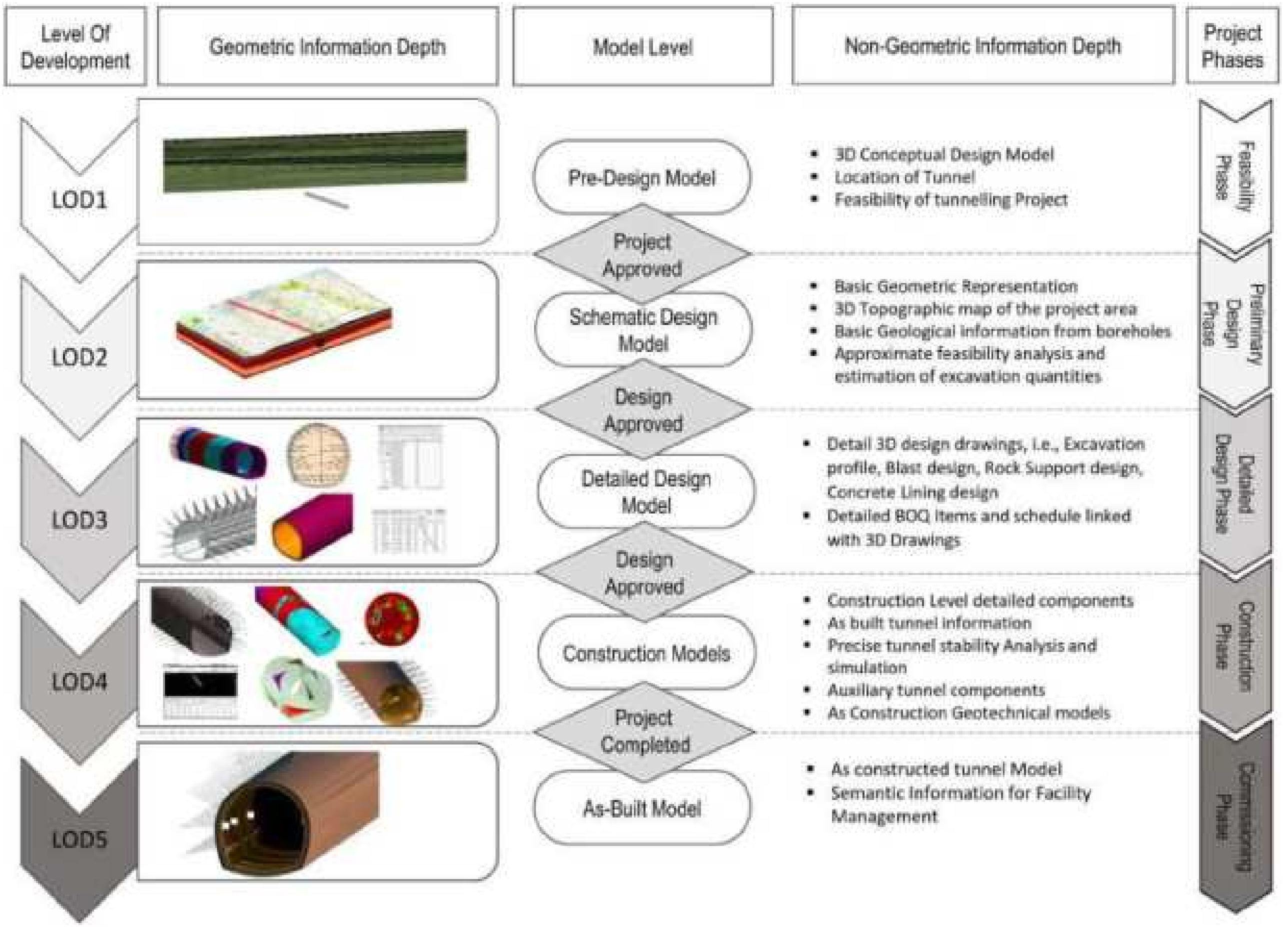

Fig. 9. Definition and representation of a drill-and-blast tunnel LOD from LOD1 to LOD5.

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with an increase in the nongeometric and geometric information as the tunnel project grows.

For drill-and-blast tunnel construction, the TIM defines five levels of development, LOD1–LOD5, presenting the TIM model level with respect to the project phases (Fig. 9). The 3D conceptual design model in LOD1 designates a footprint of the location and depth of a tunnel with respect to the surface terrain at the feasibility stage. Such information can contain the coordinates of tunnel alignment and illustrate the location of the tunnel in a 3D coordinate system. LOD2 defines the basic geometric representation of the project at the preliminary design phase. LOD2 contains borehole data, seismic survey, and topographic and basic tunnel design information, and it adds generic topographic details about the ground surface, geological information of the subsurface, and the geometry of the tunnel. LOD2 also contains a fundamental tunnel feasibility analysis and information on the excavation quantities. At the design stage, LOD3 contains detailed information about tunnel blasting, excavation quantities, geotechnical information, scheduling, cost, contract documents, and rock mass geological details. LOD3 shows the geometry of the blast rounds with a diameter and depth of the holes, and the rock mass type with all the geotechnical parameters required for the geomechanical classification of the rock. Additionally, LOD3 links all the detailed information about the schedule and cost of the project with the tunnel activities. LOD4 presents the construction-level components of drill-and-blast tunneling during the construction phase. LOD4 contains information of the as-built tunnel, encountered geotechnical information, variation orders, actual cost, and status of the project schedule. LOD4 illustrates the as-built tunnel models in terms of the excavation profile, actual ground conditions, rock support, and tunnel convergence. Furthermore, this stage shows all the auxiliary components needed during tunnel construction, such as electric power, lighting, ventilation, water, compressed air, and communication systems. Given the information from LOD3, LOD4 additionally provides a precise tunnel stability analysis, rock mass stereographic projections, and construction simulations. LOD5 contains the final-constructed information of the tunnel during the commissioning phase of the project. LOD5 depicts the final geometric information of the concrete lining and auxiliaries, depending

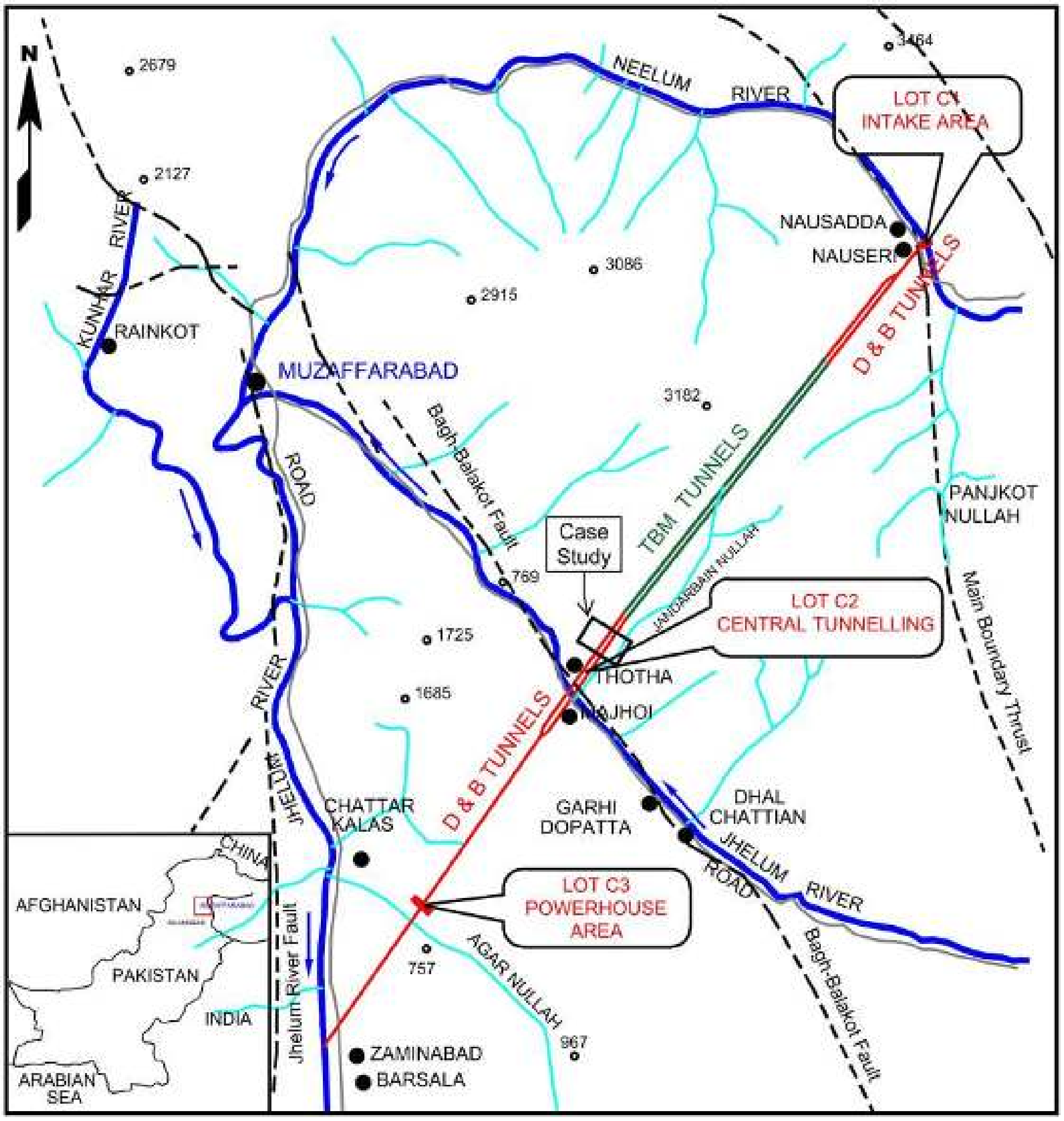

Fig. 10. NJEHP layout and regional (Northwestern Himalayan) faults.

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on the service type of the tunnel. The inspection history information is stored during and after construction of the concrete lining.

TIM Implementation and Case Study

Neelum Jhelum Hydroelectric Project

The Neelum Jhelum Hydroelectric Project (NJHEP) is a recently constructed hydroelectric project located in the Muzaffarabad district in northeastern Pakistan. It was selected as a theoretical exercise in order to validate the proposed TIM framework using the real data of the drill-and-blast project to generate meaningful output that could have helped the project. The project consisted of a 60-m-high composite (gravity and rock-fill) diversion dam on the Neelum River at the Nauseri site, a 28.5-km-long headrace tunnel with an underground powerhouse at the Chattar Kalas site, and a tailrace tunnel about 3.5 km in length that discharges water into the Jhelum River at the Zaminabad (Fig. 10). The construction of this megaproject required the setup of three different construction lots.

Located at the foothills of the northwestern Himalayas, where the infrastructure is inadequately developed, the geological setting of the NJHEP was characterized by intense tectonic deformation and the presence of extensive regional active faults. An example of these regional faults is the Balakot-Bagh thrust fault, known locally as the Muzaffarabad Fault, which was responsible for the catastrophic 2005 Mw 7.6 Kashmir earthquake. The complex geological regime was apparent during the tunneling construction by the frequent alternation of weak and strong rock units, the sometimes intensely fractured rock units that hindered the tunnel construction, and the presence of groundwater under high pressure at the crossing of the headrace tunnel under the Jhelum River.

Two-dimensional drawings are still the most common practice in the tunnel construction industry, and NJHEP was no exception. Due to their limitation in accurately presenting the physical dimensions, 2D drawings may create complications in understanding purely the geometrical characteristics of physical entities, such as the excavation and rock support, thus leading to complications in the application of the design, especially at the late stages of construction.

The identification of design problems at the construction stage is vitally important. At any later stage of the project, design problems may directly influence the project completion time, resulting in an extension of the project time and an increase in the cost of the project.

The headrace tunnel of the NJHEP comprised 19.60 km of twin tunnel sections and 8.94 km of a single tunnel section. Furthermore, the tailrace tunnel was 3.95 km, the diversion tunnel in the dam area was 0.5 km, while the cumulative length of access adits to the main waterway tunnels was around 16 km. Due to this large linear length of the project and the complex geological conditions, the tunnel construction methodology and design parameters varied throughout the tunnel alignment. Two-dimensional drawings have a limited space perspective, which causes problems in the preplanning, design, and construction of such complex projects. In this modern era of data information and modeling, TIM can compile all the 2D data acquired during the design and

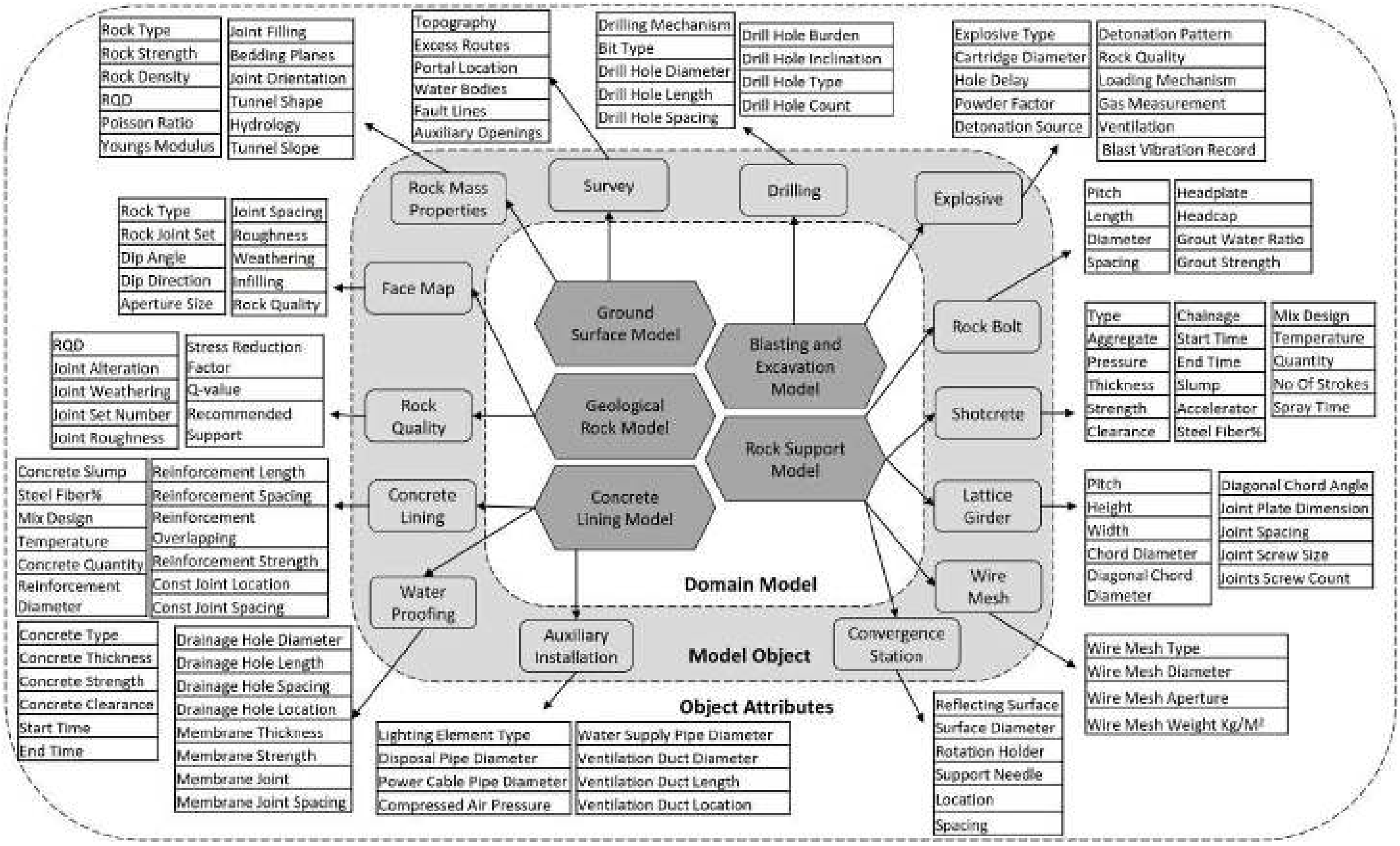

Fig. 11. View of conceptual and generic model for intelligent data models defining the subset information of the five subdomain models for the drill-and-blast process.

construction of the project for use in efficiently managing the tunnel project. A 1-km-long section of the NJHEP twin tunnel section was selected in this research in order to provide a case study scenario and verify the practical implementation of the developed TIM on a real-time tunneling project.

TIM of the NJHEP

All the data and elements of the NJHEP project are available as 2D representations in the form of spreadsheets, 2D CAD files, text documents, scanned pdf files, and images. To implement and adopt TIM in the NJHEP, all that information was modeled, interpolated, and extracted. The Autodesk BIM software Civil 3D, Revit, Dynamo, and Navisworks were used and integrated with scheduling and tunnel analysis software. The implementation of TIM comprised the following six sequential phases: (1) development of a 3D topographic model and alignment of the tunnel, (2) development of tunnel sections and tunnel construction elements, (3) 3D modeling of the tunnel with real coordinates, (4) 3D tunnel stability analysis, (5) planning and scheduling of the construction process, and (6) extraction of desired information such as quantities, costs, and 4D and 5D simulations.

Intelligent Object Modeling

A generic model in TIM is a collection of conventional intelligent data models that increase collaboration by defining the

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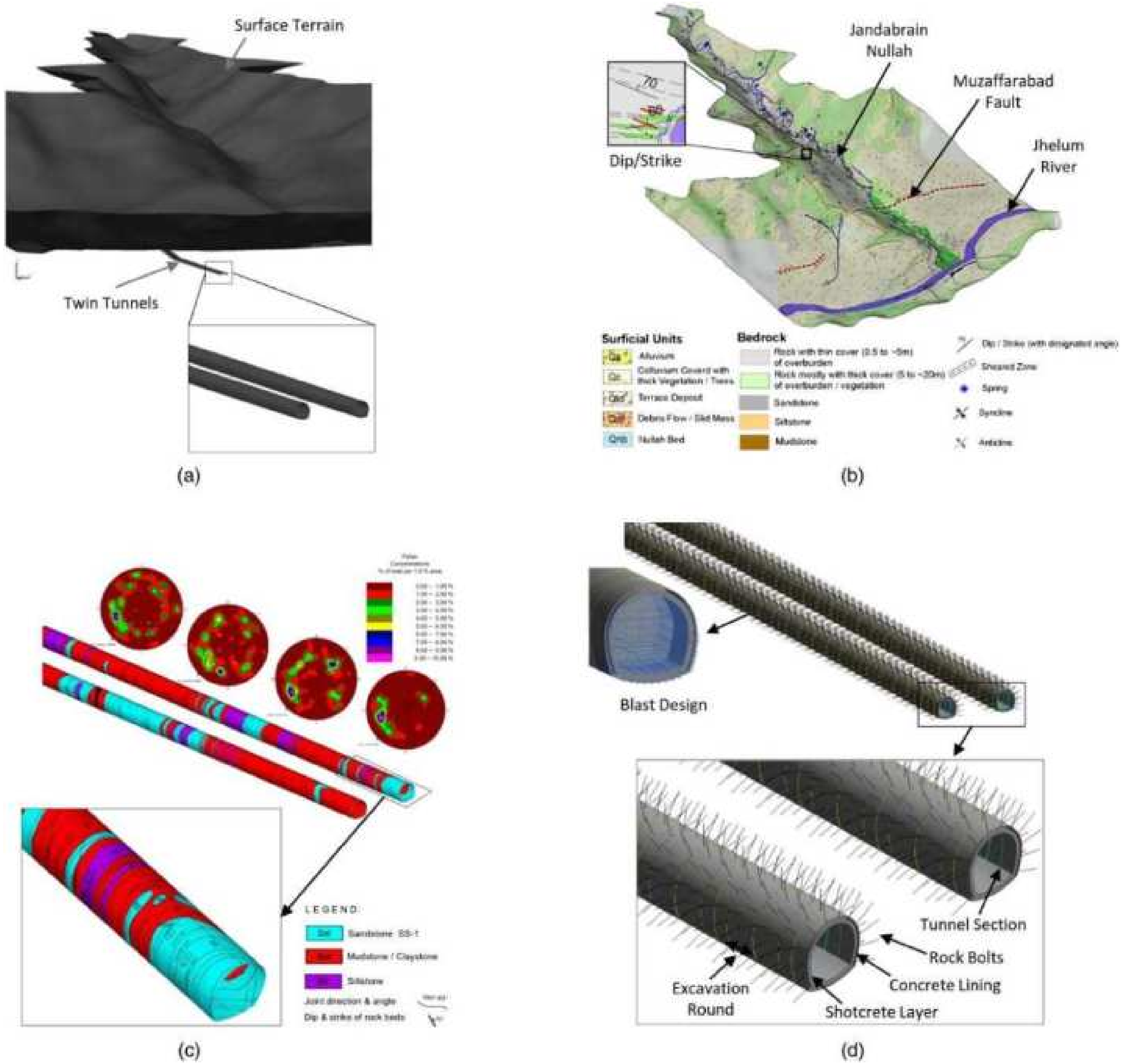

Fig. 12. TIM intelligent models of NJHEP at different LOD and construction stages: (a) 3D surface terrain information showing location and path of the tunnel; (b) detailed 3D geological and geographic information about the surface terrain; (c) geological information model; and (d) tunnel design and construction information model.

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information required to exchange information for the drill-and-blast process according to the domain-specific IFC schema. A dedicated generic model view was defined for the NJHEP case study, as illustrated in Fig. 11. The domain model view reduces the overall tunnel information model into concepts or objects and identifies a set of conceptual classes or subdomain models. Model objects are made of related objects and concepts within each subdomain model. Object attributes contain the logical data values for each object and provide spatial object attribute information to model objects.

The Autodesk Civil 3D is one of the BIM software used in the construction industry for 3D object parametric modeling. However, it does not contain built-in functions for tunnel design. For this reason, tunnel design sections were created in an Autodesk subassembly composer and integrated into Civil 3D to develop a 3D terrain surface and tunnel excavation model. Fig. 12(a) shows the excavation section of the tunnel and the project surface terrain in a 3D space created from 2D project elements, namely, the project plan, view, and profile, and the tunnel survey sheets and tunnel sections. Fig. 12(b) illustrates the detailed 3D surface geographical and geological map of the project area, which provides better visualization, data access, and control of the project area to the different stakeholders of the project, even those who are not experts in civil survey sheets and design drawings.

TIM-IFC enables intelligent TIM objects to be imported into different models and layers. The open-source visual coding software Dynamo provides a platform for creating, importing, and integrating the Civil 3D tunnel model using the same alignment and profile data in Revit. TIM intelligent object models were created in Revit to incorporate all information about the tunnel design and construction process. The geological information model contains geotechnical and geological parameters and a stereographic visualization of discontinuities orientation along the tunnel axis during excavation [Fig. 12(c)]. The excavation, rock support, and concrete lining model of NJHEP are shown in Fig. 12(d). The TIM intelligent models contain all the design and construction information while updating all the models based on the as-built information during construction.

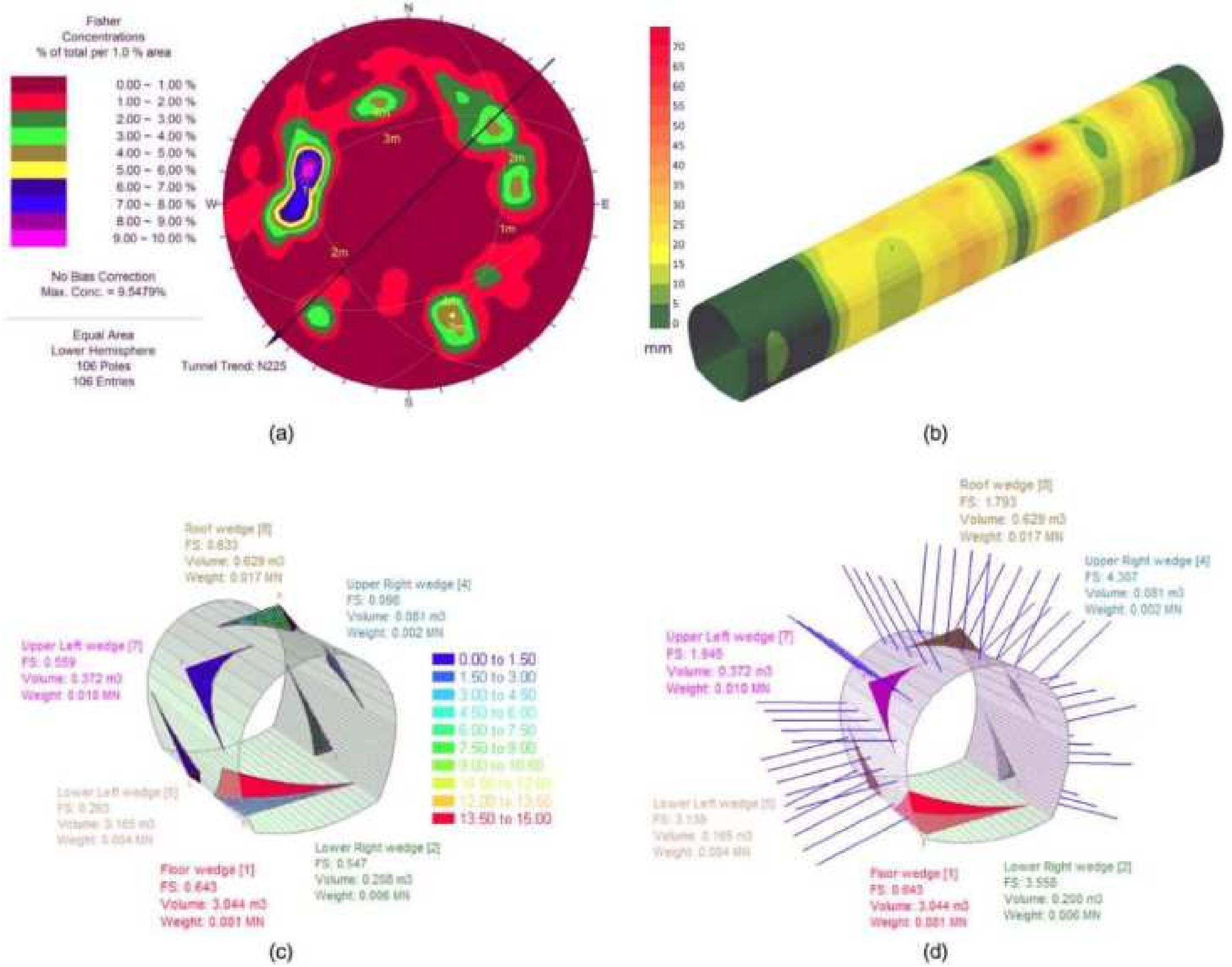

Fig. 13. (a) Stereographic projection of discontinuity-based data showing the pole concentrations of the major joint sets; (b) 3D visualization of convergence behind the tunnel face; (c) 3D stability analysis and visualization of tunnel excavation based on intersecting structural discontinuities and field stress; and (d) 3D stability analysis and visualization of tunnel excavation after applying the designed tunnel rock support.

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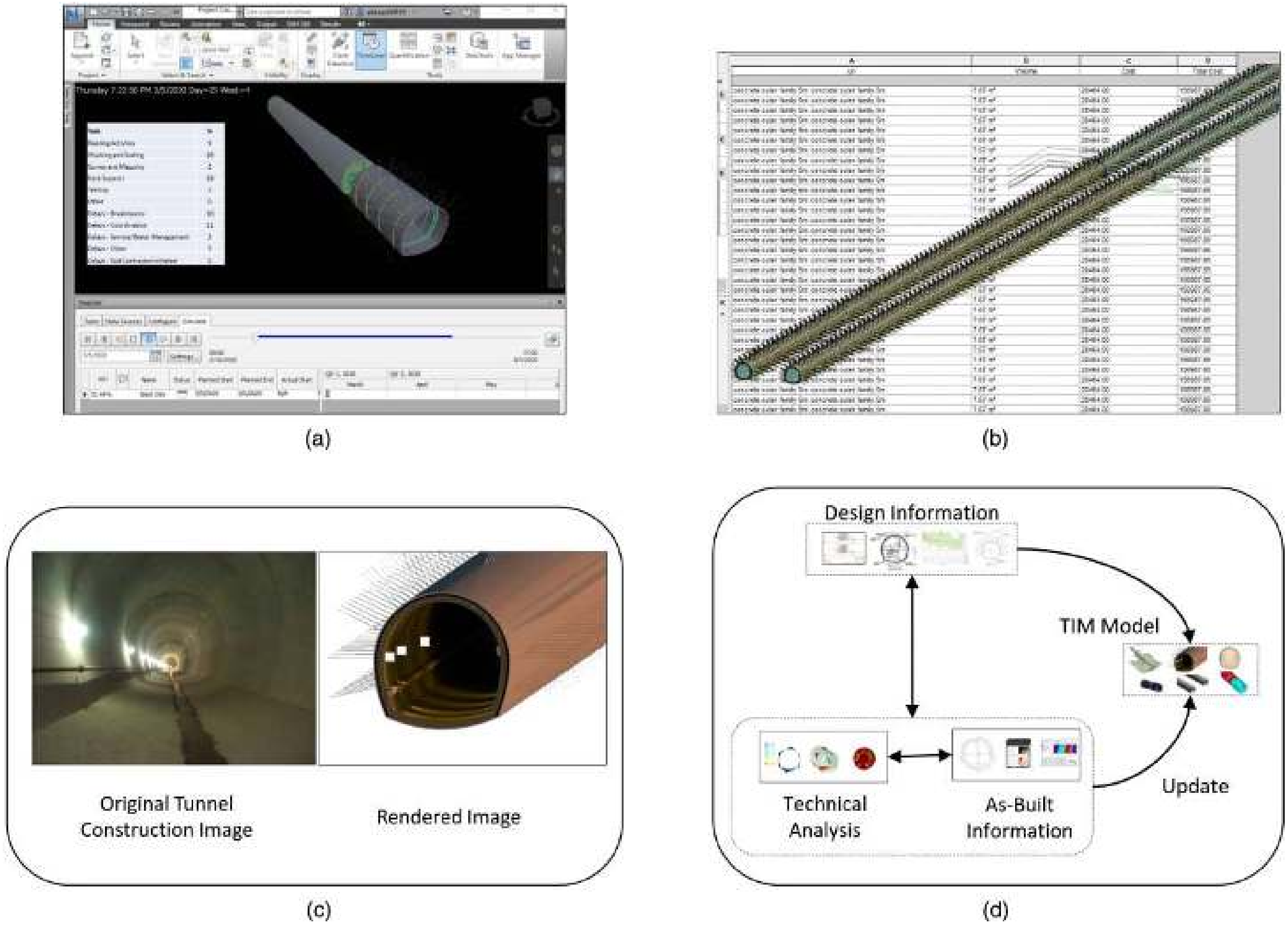

Fig. 14. (a) Screen snapshot of 4D simulation of NJHEP drill-and-blast process; (b) schematic representation of 5D model linked with quantity and cost information for the model elements; (c) as-constructed rendered image of TIM model compared with the original as-constructed image (image by Abubakar Sharafat); and (d) overall TIM process for reviewing and updating TIM models based on technical analysis.

The 4D model was developed by linking schedule and time-related information to all 3D intelligent models in Naviswork software. Six different significant activity sets, each with subactivities, illustrate the time-related information about the construction phases of the NJHEP project: survey, drilling and blasting, ventilation and mucking, installation of shotcrete, installation of rock bolts, and installation of concrete lining. Each set integrates the start and end date for each phase. For the 5D model, Revit software integrates in the intelligent models the cost-related information of every element from the bills of quantities and contract documents.

Technical Analysis

All the NJHEP information stored in the multimodeler and data source layer can help the tunnel design and construction engineers use multiple data analysis techniques and software to evaluate the tunnel stability. The integration layer links the technical analysis layer to other TIM layers through the developed TIM-IFC schema. The multimodeler provides the information needed to perform an interactive engineering analysis and stereographic visualization of the orientation-based geological data. It shows the pole concentration of the field-recorded joints and determines the major joint sets along the excavation line, giving the engineers information about the structural behavior of the rock mass [Fig. 13(a)]. A real-time convergence analysis in the multimodeler of data collected from installed convergence stations in the tunnel can visualize tunnel deformation and monitor the tunnel stability while moving ahead [Fig. 13(b)]. The 3D stability analysis and visualization of the intersecting structural discontinuities determines the unstable wedges and the induced stresses around the excavation [Figs. 13(c and d)]. They provide a real-time understanding by which tunnel designers and construction engineers can evaluate the tunneling conditions.

Application

The proposed TIM provides 3D drawings consisting of geometric and nongeometric information, including a 3D visualization of the NJHEP project, and it contains all the tunnel design models linked to its metadata. It delivers a 4D construction simulation of the project before the actual tunnel construction to visualize the schedule and conflict-related issues in planning and updates daily progress to accommodate ay necessary revisions in the schedule [Fig. 14(a)]. The 5D model offers cost-estimation feedback based on design drawings and real-time cost information from the design to the construction phase [Fig. 14(b)]. It also provides an as-constructed model of the tunnel [Fig. 14(c)]. The tunnel technical analysis links with other information to enable engineers to review and update the tunnel design drawings and models in real time [Fig. 14(d)]. In summary, TIM enables stakeholders to visualize and review design drawings, quantities, costs, and construction

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Table 3. Qualitative evaluation of TIM

Qualitative metrics	Non-TIM	TIM
2D visualization	Yes	Yes
3D visualization	No	Yes
Quantity takeoff	Manual	Automated
Material information	Basic	Detailed
Design change	Manual	Automated
Schedule conflicts	Not detected	Easily identified
Cost calculation	Manual	Automated
Phase planning	No	Yes
Design coordination	Manual	Automated
Data sharing	Manual	Automated
Model base analysis	Individual	Integrated

Table 4. Quantitative evaluation of TIM

Quantitative metrics	Identified using TIM	Actual during project construction using non-TIM
Schedule conflicts	39	48
Design errors	21	21
Reworks	26	32
Variation orders	10	12
Data conflicts	23	25
Excavation planning	42	42
Safety accidents	15	17

information and optimize them in real time while providing feedback to tunnel designers, project managers, and construction engineers during design and construction to support decision-making and risk assessment for the drill-and-blast construction of NJHEP.

TIM Evaluation

BIM effective evaluation methodologies are diverse and based on the BIM benefits for individual projects (Barlish and Sullivan 2012; Won and Lee 2016; Zhou et al. 2017). For the evaluation of the proposed framework considering the objective and goals of this study, qualitative and quantitative evaluation was performed to determine the benefits of TIM versus non-TIM. A theoretical TIM case study of a 1-km section of a tunnel project was compared with actual tunnel construction of 1 km of the same section of tunnel that was constructed using non-TIM. The qualitative TIM evaluation matrix was based on the objective of the TIM goal and uses in the drill-and-blast tunneling industry compared with non-TIM (Table 3). For quantitative TIM evaluation, actual non-TIM project data was analyzed, and the number of project issues that were schedule conflicts, design errors, reworks, variation orders, data conflicts, excavation planning, and safety accidents due were quantitatively measured. These issues directly affect the project cost, completion date, and quality. Then individual interviews of 12 project managers, engineers, and designers responsible for decision-making in NJHEP, all having a minimum of 10 years of experience in the drill-and-blast tunneling industry, were conducted to identify the potential of the proposed TIM to identify these issues at the right phase of the project. Project participants agreed that TIM provides opportunities to identify and rectify the mentioned issues at the right time instead of after the completion of construction activity (Table 4).

Conclusions

The drill-and-blast tunneling method involves multidisciplinary activities that both generate and require a large amount of engineering data and information from the design to the construction stage. Digitization of data has become a necessary process to improve project management, construction, and delivery. In particular, the integration and interaction of information from design, technical analysis, and construction processes need to be managed efficiently to enable a successful drill-and-blast tunnel project. BIM technology has become an important part of digitizing construction information; however, it remains immature in the tunneling industry.

This paper has proposed a BIM-based TIM framework to visualize, manage, and simulate the drill-and-blast tunnel construction process. Due to the distinctive nature of tunnel design and construction activities, a multimodel framework has been adopted to develop five intelligent models. These models are linked with open IFC platforms for data standardization, management, and interoperability. An implementation case study on real project data has been conducted to validate the TIM's potential and advantages.

The contribution of that research to the main body of knowledge is a generic TIM framework, its implementation, and validation that allows (1) real-time data use, (2) effective information integration, (3) modeling of interdependent activities, (4) tunnel design analysis and review, (5) visualization of data, and (6) BIM-based project management for drill-and-blast tunneling. Furthermore, this research provides a guideline for the geometric levels of details required using LODs based on project activities. Also, it proposes a new IFC standard for drill-and-blast tunnel construction components, enabling international BIM professionals to provide better data interoperability for tunnel projects. The proposed TIM-IFC follows the guidelines laid out by buildingSMART International, and new entities are only defined when the existing entities do not provide the semantics required by the tunnel construction process.

While this proposed framework has significant benefits for managing drill-and-blast tunneling projects, it also contains some limitations. This framework considers the major drill-and-blast tunneling activities and the IFC-based model for major tunnel components, depending on the geotechnical conditions needed. For example, in the case of tunneling through highly saturated weak zones, tunnel activities such as the installation of spiles, steel ribs, pipe canopy, and grouting may be needed. Another limitation of this study was in managing the distortions of the geographic coordinate system in object-based modeling software such as Revit. The proposed framework has been applied to a 1-km section of the tunnel project, and georeferencing the origin of the local model in a case study was performed to address this issue. However, object-based modeling software products are developed for building projects, and in the long tunneling project, there is a distortion between real-world lengths and dimensions and those of the model. Another challenge is that there are only small sets of BIM software that can utilize the TIM data model introduced in the study. In addition, BIM software mostly includes templates and families specific to building projects. The design of new generic tunnel families and parameters can be tedious work in the absence of tunnel-specific definitions. To address this issue, a BIM application programming interface (API) can be used in the future for API definitions and formatting, including for tunnel construction templates and families based on various tunnel parameters and relationships.

Finally, the proposed BIM-based TIM framework has excellent potential to enhance construction management, risk assessment, and decision-making from the design to the construction phase of drill-and-blast tunneling. It can increase collaboration, data accessibility, interoperability among engineering disciplines, and spatial coordination. However, the proposed framework has some limitations that can be improved in the future by integrating the latest data collection and processing technologies, API, and developing a web-based TIM collaboration platform.

Appendix I. Extract of EXPRESS-G Diagram

Fig. 15 shows the extract from the EXPRESS-G diagram of the IFC-based data model for the drill-and-blast tunnel construction. IFC-Tunnel has five parts: IfcSurfaceandGroundModel, IfcBlastingandExcavationModel, IfcGeologicalRockModel, IfcRockSupportModel, and IfcConcreteLiningModel. It also illustrates all the attributes of IFC-Tunnel classes.

Appendix II. UML Diagram

Fig. 16 provides a UML class diagram that depicts a static structural diagram of the IFC-Tunnel by showing all classes, their attributes, and relationships among these classes.

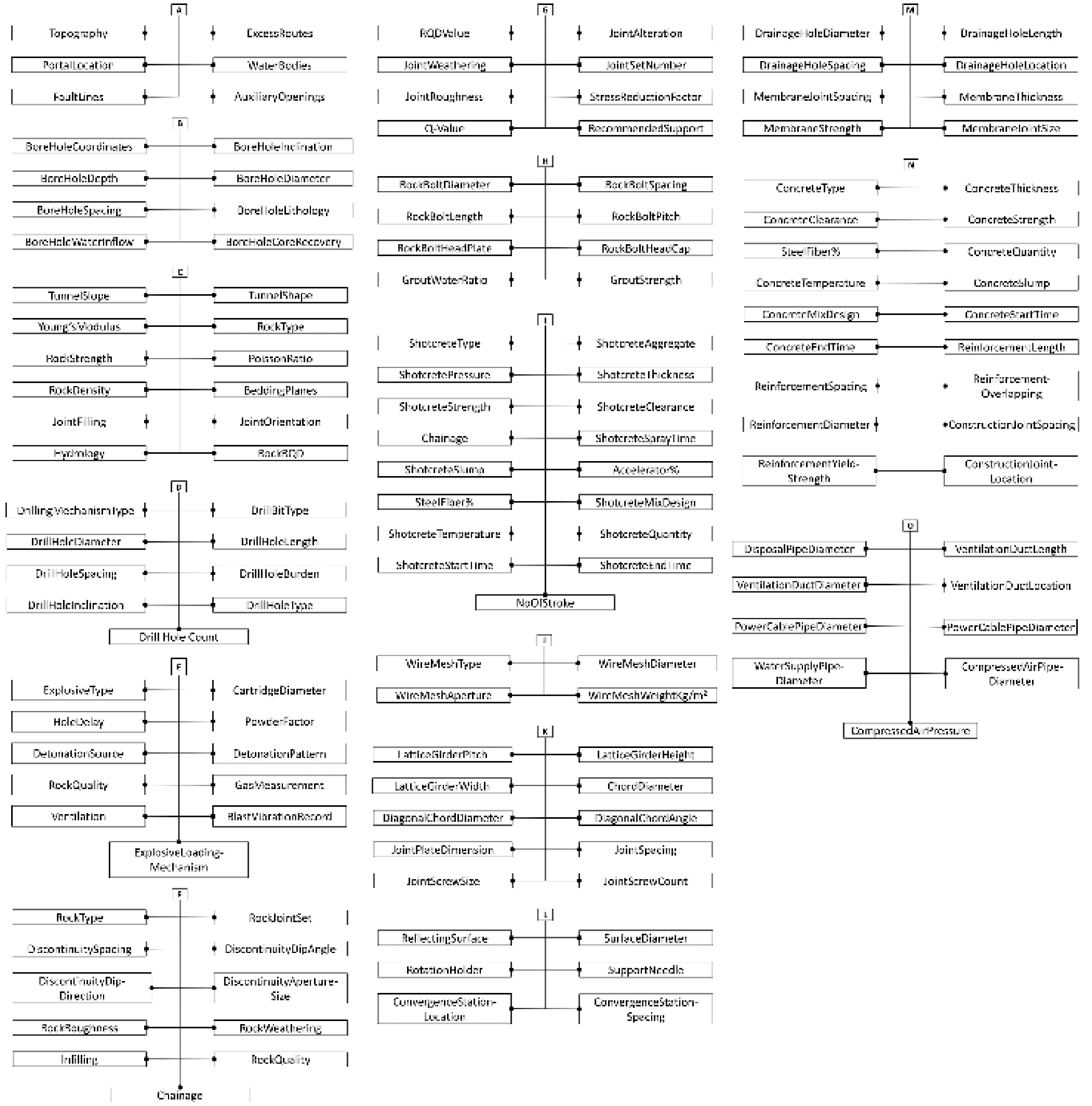

Fig. 15. Extract from the EXPRESS-G diagram of the IFC-based data model for drill-and-blast tunnel construction.

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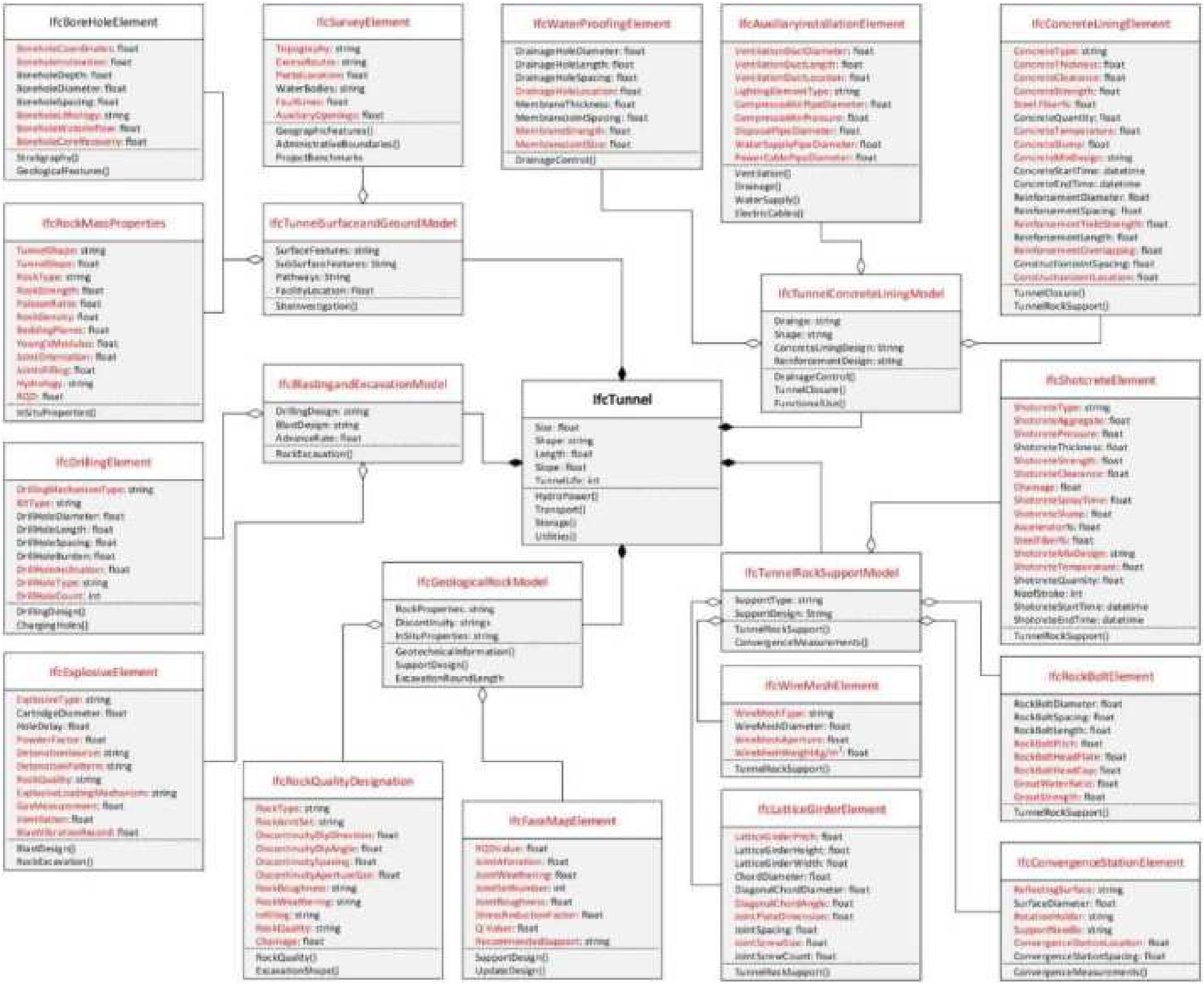

Fig. 16. UML class model depicting all the proposed and existing classes along with their attributes.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. The available items are TIM data models and code generated in this study with the restriction of NJHEP case study construction information.

Acknowledgments

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Supplemental Materials

The EXPRESS definition is available online in the ASCE Library (www.ascelibrary.org).

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