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A formal representation of data exchange for slope stability analysis of smart road design and construction

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Abstract: The Industry Foundation Classes (IFC) provides standardized product models for the building construction domain. However, the current IFC schema has limited representation for infrastructure. Several studies have examined the data schema for road and highway modeling, but not in a sufficiently comprehensive and robust manner to facilitate the overall integrated project delivery of road projects. Several discussions have focused on slope engineering for road projects, but no solution has been provided regarding the formalized parametric modeling up to now. Iterative design, analysis, and modification are observed during the process of slope design for road projects. The practitioners need to carry out the stability analysis to consider different road design alternatives, including horizontal, vertical, and cross-section designs. The procedure is neither formalized nor automated. Thus, there is a need to develop the formal representation of the product and process of slope analysis for road design. The objective of this research is to develop a formal representation (i.e., an IFC extension data schema) for slope analysis. It consists of comprehensive information required for slope analysis in a structured manner. The deliverable of this study contributes to both the formal representation of infrastructure development and, further, the automated process of slope design for road projects.

Key words: Building Information Modeling (BIM), Industry Foundation Classes (IFC), slope stability analysis, civil infrastructure modeling, interoperability, smart design and construction

1. INTRODUCTION

Due to land scarcity and development in urban regions, natural and artificial slopes are common alongside infrastructure, especially in Hong Kong, where the land value is extremely high. The hilly terrain in Hong Kong provides a large number of slopes, inevitably posing threats to the infrastructure and surroundings. According to the Highway Slope Manual published by the Hong Kong government [1], an estimated 166 landslides—some resulting in fatalities—reportedly affected roads from 1984 to 1998, mainly involving artificial slope features.

To ensure the safety of slopes, iterative design, analysis, and modification are observed in the road design process, especially when the slope is not stable enough in its natural state. Practitioners need to carry out stability analyses repeatedly to examine the design alternatives of horizontal, vertical, and cross-section plans. The drawbacks of the modeling process are apparent. First, the whole procedure is neither formalized nor automated. The practitioners experience subjective and arbitrary decisions. Second, the inconsistent procedure is a hurdle to the integrated project delivery. Third, during the analysis, the remodeling process can result in information mismatch and loss. Thus, it is crucial to formalize the digital repository, representation, and automated process of parametric modeling for infrastructure.

Researchers have been working to improve the interoperability of building information modeling (BIM). Commercial software vendors provide comprehensive representations specifically tailored to the software, but with limited compatibility. In this case, the practitioners have developed various types of commercial software to carry out even the analysis in one aspect. The remodeling process in each analysis is problem-prone due to the inconsistent, repetitive, and redundant procedure. Openness is the critical success factor of integration and interoperability [2]. Open standards and specifications have been promoted to provide a digital repository of components and relationships related to building projects. The Industry Foundation Classes (IFC) is an example, which has been widely adopted in the architecture, engineering, and construction (AEC) industry The IFC schema is a standardized data model that codifies a variety of AEC related objects in a logical way, providing a comprehensive repository of objects, properties, relationships, amongst others with an open protocol [3]. With the aid of IFC, the exchange process is more organized and smoother for better integrated project delivery. Software is expected to extract the desired information package through the model view definition (MVD), which is a subset of the IFC schema. The application of MVDs has been deployed in areas of energy simulation, structural analysis, etc. Although discussions on the whole process of application of open standards are still ongoing, the building industry has gone beyond other domains in the broad AEC scope in its parametric modeling with open standards.

Despite the application of open standards in the building industry, open standard parametric modeling in civil infrastructure is still in its infancy. Although software vendors like Autodesk and Bentley have published infrastructure-related tools for years, the interoperability of the infrastructure model and corresponding analyses is poor. IFC can also represent infrastructure components by mapping components to building components; however, it is problematic due to the mismatch of functionality and semantics [4]. The current IFC schema, IFC4x3, provides limited information restricted to road components. There is a need to extend the data schema to geotechnical representation and slope-related components in a standardized manner.

In this research, we pose the research question to ask how we can formalize and automate the process of slope design for road projects; one of the research objectives to answer this question is to develop the formal representation of information needed for slope analysis, which is discussed in this paper. Section 2 covers the existing literature on how open standards can help the building and infrastructure domain as well as slope-related research specifically. Section 3 explains the formal representation proposed and its development methodology. Section 4 summarizes the conclusion of this paper and suggests areas for future work.

2. LITERATURE REVIEW

IFC, as the most comprehensive and popular open exchange format of BIM, was originally designed to represent the building construction context. It is an established generic information exchange standard for BIM and has been supported by most of the BIM software in the AEC industry [4]. Compared with CityGML, which is specified as Extensible Markup Language (XML) [5], IFC is an object-oriented data schema, first defined by the data modeling language EXPRESS. Later, IFC also developed an XML version (i.e., IfcXML) and other variant carriers. However, IFC did not support any infrastructure-related entities until the release of IFC 4, when some geographic elements were related to GIS. By the release of IFC 4x3 [6], several infrastructure domains were included (e.g., IfcRoad, IfcRailway, IfcMarineFacility). However, the support to infrastructure is still limited by IFC 4x3 as it is still in the preliminary phase of IFC supporting infrastructure representation.

Due to the lack of formal digital representation for infrastructure, researchers have proposed data schemas and prototypes for infrastructure. Several reviews have summarized the existing works of data schema developed [4, 7, 8]. Despite their different perspectives of discussion on BIM for infrastructure, domains like roads, tunnels, bridges, and railways—namely the fundamental transportation infrastructure—have attracted considerable attention.

Roads/highways were one of the earliest domains with data schemas developed in the infrastructure industry. The IFC-Road project was proposed at the IFC Bridge & Roads workshop as early as 2005 [4, 9]. Aritomi et al. [10] created a road information model with alignments, profiles, and cross-sections based on parametric geometric modeling. Tunnel models have also been a research trend, with most of the studies being developed as IFC extensions with both conceptual and semantic models [11-13]. Koch et al. presented the most comprehensive data schema for the design and construction phase of tunnel projects. Bridges are another research interest of scholars. Borrmann et al. [14] applied the process map suggested by the Information Delivery Manual (IDM) to identify the exchange requirements for bridge design and construction. For bridge maintenance, Sacks et al. [15] proposed an IFC extension regarding bridge inspection in the maintenance stage of a project, providing new insights for academia and the industry.

As discussed in Section 1, the slope stability analysis is crucial for linear infrastructure (e.g., road and railway projects). De Vallejo and Ferrer [16] claimed that slope stability is determined by geometric factors (e.g., height and angle), geological factors (which dictate the presence of surfaces and areas of weakness and anisotropy on the slope), hydrogeological factors (related to the presence of water), and geo-mechanical factors (strength, deformability, and permeability). Other potential factors are static and dynamic loads, precipitation and climatic regime, and weathering processes. GEO [1] concluded that the geotechnical review for highway projects needs to take topographical, geological, hydrological, and groundwater conditions into consideration.

Few existing studies have explored the information related to slope analysis. Jung and Chung [17] proposed an ontology-driven slope modeling method considering disaster management. Yue et al. [18] first showed ontology-based geospatial semantics with prototype validation from the GIS perspective, involving slope representations by DEM. Existing research has considered data schemas related to slope modeling from different perspectives, but no studies have included the information needed for the analysis process; thus, none of the schema are tailored for executable analyses. In addition, the proposed schema did not support interoperability among platforms, and some only provided relationships without semantics.

To sum up, BIM is not restricted to buildings; it can also be successfully adopted for civil infrastructure. However, the lack of digital repositories adds to the difficulty of integrated project delivery in lifecycle management. Some research has examined data schema for roads/highways, but it is still not comprehensive or robust enough to facilitate the overall integrated project delivery. Specifically, existing studies have limitations in formally and comprehensively representing information required for the slope analysis of road projects.

3. IFC EXTENSION DEVELOPMENT

The research methods generally follow the IDM process of buildingSMART [19, 20]. The formal representation of the data schema has been developed as an extension to the existing IFC schema. The development process of an IFC extension data schema consists of several steps. A process map and several use cases are the first step to identify the information exchange requirements. Conceptual modeling is then followed to formalize the proposed classes, attributes, and their relationships collected from the exchange requirements. The IFC extension follows the structure of the conceptual model and is aligned with the existing IFC standard. After the development process of an IFC extension, the proposed data schema provides representations for the slopes and surroundings of a road design.

3.1. Process map

As the first step in developing a data schema, the process map recognizes and describes the information flow and captures the information exchange process in a general manner. All involved stakeholders and potential data exchange requirements are identified during this step. A partial extract of the process map shown in Figure 1 depicts the information exchange process of a slope analysis for a road project. In practice, the alignment of the road is first tentatively selected, while the slope stability along the road is considered in addition to the design, with further geotechnical information acquired from site investigation, laboratory tests, and so on. If the slope stability analysis results, e.g., Factor of Safety (FoS), indicate a stable design, the road design will be accepted considering the slope stability perspective. However, this is usually an iterative process when the tentative design does not meet the stability requirements and, thus, needs further modifications. Additional analyses and information are needed until the analyses show satisfactory results. This process involves several information exchange items, including the road design, the cross-section extracted from the design, and additional information needed for the stability analyses. The iterative process also considers the feedback of stability; however, this is not considered in the current scope of the data schema for slope stability analysis.

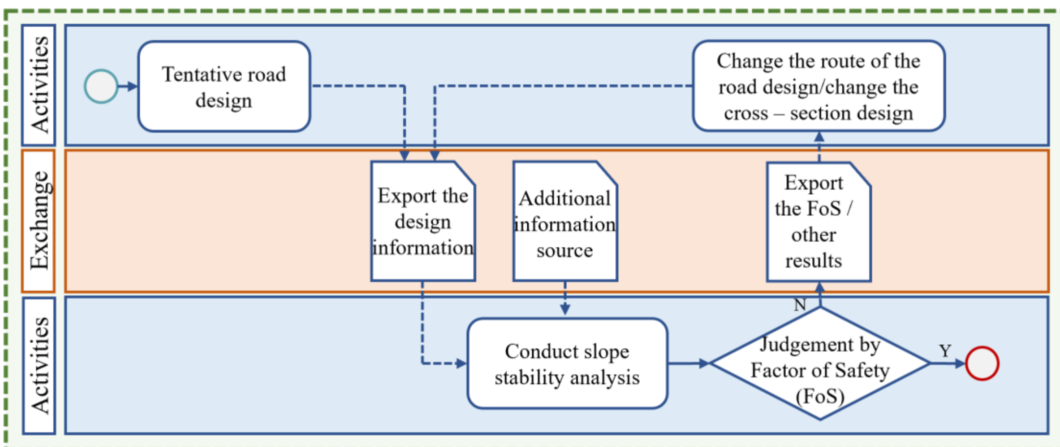

Figure 1. An extract of the process map identifying the information exchange process

3.2. Use cases

The use cases identify the need for information exchange scenarios, including the demand for exchange and interoperability during the process map. For example, in this study, the process may involve different dimensions of information requirements for future applications, when use cases identify the exact needs during practice. The use cases investigated during this study are listed in Table 1. The variety in use cases ensures the comprehensiveness of the data schema. Due to the potential differentiation in using analysis methods, a slope analysis using the limited equilibrium (LE) method and finite element (FE) method are considered in use cases 1 and 2, respectively. The difficulties and costs involved in acquiring holistic ground conditions are common; thus, use cases 3 and 4 cover the circumstances of different information availability.

Table 1. Use cases to identify the information exchange requirements

No.	Name of the use case	Description
1	Slope analysis with LE	This use case considers information needed for the limited equilibrium method for slope analysis.
2	Slope analysis with FE	This use case considers information needed for the finite element method for slope analysis.
3	Slope analysis with comprehensive 3D underground conditions	This use case considers the case when underground information is fully accessible and comprehensive, including the predicted underground conditions.
4	Slope analysis with limited information	This use case considers the case when ground conditions are insufficient, and information for analysis can only be available for cross-sections needed.

3.3. Conceptual model

The conceptual model describes the classes, attributes, and semantic relationships for the data schema. Apart from the requirement analyses mentioned in Sections 3.1 and 3.2, additional classes and attributes are collected from geological knowledge-based references [1, 16] and commercial slope analysis tools. Figure 2 shows an illustrative view of the integrated information container. Four blocks of information are involved: geometry representations and road project basics, geological conditions, geo-mechanical properties, and hydrological conditions.

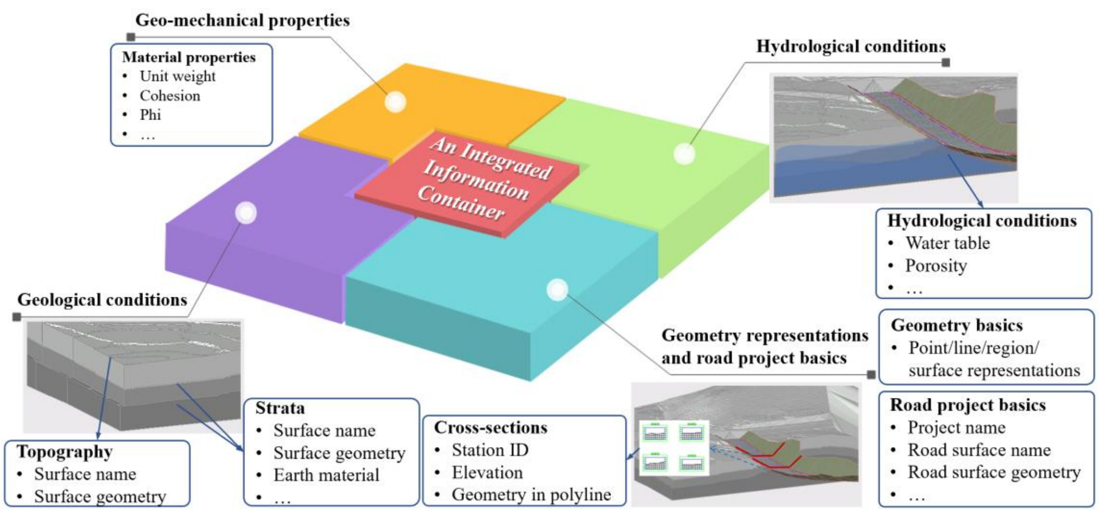

Figure 2. An illustrative view of the integrated information container

Although there are several ways to develop the conceptual model, Unified Modeling Language (UML) is selected for this study due to its richness and comprehensiveness of expression and the convenience of mapping to other data schema expressions.

Figure 3 is the UML model for the proposed data schema, showing the association and inheritance relationships among entities, while detailed attributes have been hidden for clarity. According to the variety of information availability, we include both 3D representations of the ground conditions and 2D representations of information ready for cross-section slope analysis. When the information on surrounding ground conditions is insufficient, the cross-section information directly serves for slope stability analysis, when 3D representations are not involved. In the case of situations with sufficient knowledge on underground situations or well-predicted subsurface conditions, the 3D representations could represent the data comprehensively, while cross-section information needed for slope stability analysis inherits directly from 3D representations, providing great flexibility and comprehensiveness to the data schema.

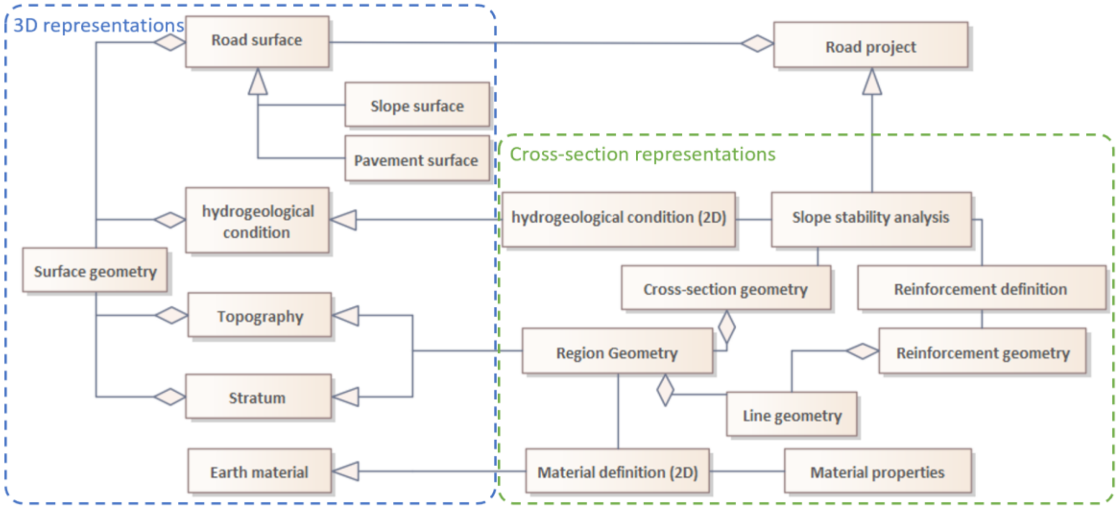

Figure 3. An extract of conceptual model in UML

3.4. IFC extension

The IFC deliverables consist of many variants. In the study, IFCDOC is selected as the tool to align the extended schema to the existing IFC schema. IFCDOC enables a graphical view of the data schema, while adding and editing entities are explicit. In addition, it is also possible to export both the EXPRESS and XSD formats for the extended data schema, which provides flexibility for further application and validation. IFC 4 ADD 2 is selected as the baseline for extension.

Applying the conceptual model to the IFC extension involves reusing entities and property sets. It is important to align the newly developed items with the existing schema in a seamless and concise manner. An extract of the extension regarding material definition and properties in resource layer of IFC schema is shown in Figure 4 as an example. The dark gray items are those included in IFC 4 ADD 2, while the light gray ones are newly added. The current IFC schema allows three ways of material definition, i.e., by layer, by profile, and by constituents. A new material definition method is added with the entity *IfcMaterialRegion*, to enable cross-section-based material definition by region. The entity *IfcGeomechanicalPeroperties* includes examples of geo-mechanical properties for the slope analysis. The material definition can be assigned to the objects by using the objectified relationship *IfcRelAssociatesMaterial*.

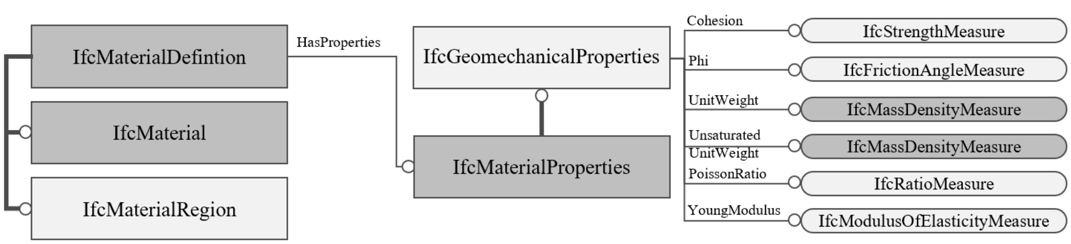

Figure 4. An extract of the IFC extension in EXPRESS-G

3.5. Discussion

The developed IFC extension provides a comprehensive representation of the information needed for slope analyses of road projects. However, an information portal is still needed to execute the exchange process. With the information exchange portal, information from multiple data sources can be integrated via the newly developed IFC extension data schema. A prototype can facilitate the actual data exchange process through the newly developed IFC extension, and a user-friendly interface can provide essential functions to help select intended information exchange activity for the designated slope analysis requirements. The prototype also functions as a platform to validate the data schema, by presentation, visualization, and the carrying out of analyses.

4. CONCLUSION

Researchers have been working on improving the interoperability of BIM. IFC, which provides a standardized product model for the design and construction of buildings, has been widely adopted in the AEC industry. The current IFC schema (i.e., IFC 4x3) has limited representation for infrastructure. There is a need to extend the data schema to represent detailed information for infrastructure in a standardized manner.

Studies have examined the data schema for road and highway modeling, but they are still not comprehensive or robust enough to facilitate the overall integrated project delivery of road projects. In terms of the slope design, no research has yet explored the formalized parametric modeling. Iterative design, analysis, and modification are observed in the process of slope design. Practitioners need to repeatedly carry out stability analyses to consider different road design alternatives, including horizontal, vertical, and cross-section designs. Thus, a formal representation of the information needed for the slope analysis of road projects will help.

This research follows the IDM process to develop an IFC extension. First, exchange requirements are identified through the process map and use cases. We then propose the conceptual model using UML and implement the conceptual model for IFC extensions. The outcome of this study is the formal representation of information needed for slope stability analysis. The IFC extension functions as a medium to carry out the information exchange process and will largely contribute to the geotechnical and slope representations of the IFC schema while enhancing interoperability for further applications. This will further improve the efficiency of design and construction process of civil infrastructure industry.

The future research scope could be extended to the automated slope design process for road projects, with the rationale of human decisions, where the formal representation of slope functions as a carrier, promoting the better integrated project delivery. In addition, an evaluation framework can help quantify the improved efficiency brought by extension and the automated process.

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