A BIM-based Ground Information Management (GIM) Framework to Manage Ground Risk for Construction Projects

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Abstract

Infrastructure design and construction in Hong Kong typically adopt a project-based process that is highly siloed and labour intensive. However, the successful delivery of construction projects in the digital age demands effective communication of the geological and geotechnical conditions through seamless ground information management and transfer. The requirements for Level 2 Building Information Modelling (BIM) approaches on engineering projects have driven a large-scale digitalization of the construction industry in recent years. However, geotechnical aspects have often remained neglected. To address this, mechanisms are proposed to incorporate ground information in BIM and ensure better ground risk management throughout the project life cycle. This paper reviews the current geotechnical context in terms of existing BIM standards and introduces a BIM-based ground information management (GIM) framework through Common Data Environments (CDE). This allows information-driven ground knowledge and management by clearly defining information requirements, adopting local classification systems, and developing project-specific level of information needs (LOIN). Through the BIM approach, ground uncertainty and risks are conveyed by introducing Level of Certainty (LOC) and Risk Registers linked through geometric information, LOIN, and metadata.

Keywords: BIM, Ground risk, Risk registers

1 Introduction

1.1 Introduction of Ground Modelling for AECO Industry

Ground modelling plays an indispensable role in engineering projects, directing downstream planning, design, and construction and having significant bearing on overall costs. Indeed, several studies have shown that “unforeseen ground conditions” resulted in over a third of construction project overruns or failures due to the incorrect use or development of ground models (Morin, 2019). Based on *The next normal in construction* (McKinsey Global Institute, 2020), the construction ecosystem will be reshaped by digitalization of products and processes to form a more standardized and integrated system. This echoes the recent emergence and mandate for adopting Building Information Modelling (BIM) in the local construction industry. However, although gaining traction through widespread adoption, the sector still lacks a well-defined framework for the management of ground information in a BIM environment. This is particularly so regarding data standards, technology, and information layers.

The successful deployment of construction projects requires models that have been built through the seamless integration of knowledge and data between both geology and engineering. Such models are

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described as Engineering Geological Models (EGM) (Baynes et al., 2020) [or Ground Model (GM) in this paper]. The GM can be seen as a critical knowledge hub for risk management, solving engineering problems, aiding engineering decision-making, and identify project opportunities throughout the project lifetime (Baynes et al., 2010; Parry et al., 2014; Kessler et al., 2015; Daly et al., 2019; Baynes et al., 2020).

1.2 Existing Ground Information Management (GIM) System

Holistic modelling of the ground involves interpreting data from various sources and formats (GEO 2007; Pan et al. 2012). These can be categorized into i) *direct data* from site mapping, ground investigation (GI), or laboratory tests, ii) *indirect data* from the interpretations made by others, including technical reports and geological maps, and iii) *auxiliary data* that aids the inference of available ground information such as satellite images, aerial photographs, topographic maps, historical maps, as-built drawings, etc. (Mak et al., 2019).

In Hong Kong, much of the above-ground data has been centralized within a cloud-based national database, namely the "Geotechnical Information Infrastructure (GInfo)" managed by Geotechnical Engineering Office (GEO) (Lai et al., 2019). Similar practices to this are also adopted in places like the UK and the US, where GI data can be downloaded in unstructured formats such as PDF as well as structured formats like AGS or DIGGS (Daly et al., 2019; Gilder et al., 2020). The AGS and DIGGS formats comprise standardized geospatial schemas for the electronic exchange of geotechnical data developed in 1992 and 2006, respectively. Their use allows the transfer of geotechnical data across borders in a manageable and structured manner and unleashes potentials for reusing digital data.

1.3 Current Issues in Ground Information Transfer

The increasing use of BIM means that the significance of GIM has come to the forefront once again, in particularly regarding the incorporation of both factual and interpreted geotechnical data (Antoljak, 2015; Kessler et al., 2015; Tawlian & Mickovski, 2016; Chadwick et al., 2019; Baynes et al., 2020). In this respect, several key issues and challenges have been identified.

While electronic transfer formats are available for GI data, a vast amount of ground information is still commonly transferred as unstructured data in the form of paper records, PDF files, or Computer-Aided Design (CAD) files (Antojak, 2015; Daly et al., 2019; Gilder et al., 2020). These formats are all static, imposing limitations on their transmission and re-use, and forming silo workflows (Antoljak, 2015). To overcome this, the data within the files must be re-processed through data re-entry and reworking to more versatile and standardised formats (Antojak, 2015; Daly et al., 2019; Gilder et al., 2020).

Although the AGS format enables the transfer and reuse of data, the current format is limited to factual data. This diverges from the BIM environment, where geometric and interpreted information is hosted (Kessler et al., 2015; Chadwick et al., 2019). This limitation is being addressed to some degree by recent computational advancements in geological modelling like 3D implicit ground modelling using algorithms. However, such 'algorithmic geometries' are often regarded as the 'truth' without conveying any of the underlying uncertainty associated with them (Baynes et al., 2020). There is also no standard schema currently available for geological models to facilitate the digital transfer of both the geometries and attributes in a consistent manner (Chadwick et al., 2019), which is one of the keys to successful BIM implementation. To address this, this paper proposes a GIM framework that will help maximize the value of ground data and enrich the wealth of ground knowledge in a BIM environment.

1.4 BIM Implementation in Hong Kong

According to ISO 19650-1:2018, BIM is defined as the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions (BSI, 2018). It aims to support the project or organization objectives using information management processes initiated by information requirements (Figure 1).

Since 2013, the Hong Kong Government has explored BIM technology for both public works and asset management. In the latest Technical Circular (Works) No. 12/2020 by the Development Bureau (DEVB), most BIM uses have become mandatory throughout all design and construction stages of a project. As a result, various BIM-related task groups have been established within the government departments and institutes such as the Construction Industry Council (CIC). The drive for BIM implementation by the government has been promising and has resulted in the development of the BIM Data Repository Platforms prototype by Lands Department (LandsD), BIM Integration with GInfo by CEDD, and the Electronic Submission Hub (ESH) by the Building Department (BD). In this respect, it is noted that Stage 2 of the ESH development will accept plans for geotechnical works, including foundation, site formation and excavation lateral support (ELS) in 2022 to 2023.

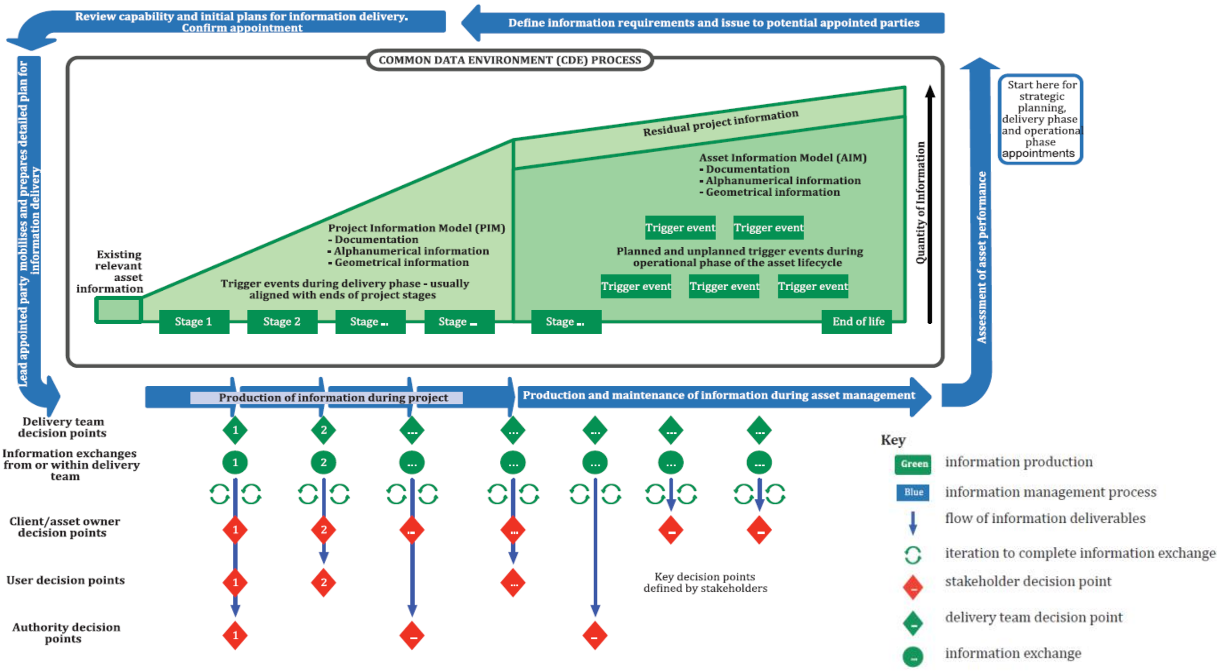

Figure 1: Process of BIM according to ISO 19650-1:2018 (BSI, 2018)

2 Principles of BIM-based GIM for Construction Project

2.1 Introduction

While there has been a recent surge in BIM use in the AEC industry, subsurface information remains somewhat neglected and lags behind data for other construction aspects (Kessler et al., 2015; Morin, 2019). However, the emergence of advanced technologies is disruptively transforming ground modelling practice through digitalization, opening up its potential for an enhanced BIM-based GIM

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(Antoljak, 2015; Kessler et al., 2015; Tawlian & Mickovski, 2016; Daly et al., 2019; Baynes et al., 2020; Gilder, 2020). This will provide notable benefits to the industry, yielding a whole-life ground risk management tool that complies with the existing BIM processes and better manages ground data as an asset.

2.2 BIM as a Whole-life Ground Risk Management Tool

The ground model is a key knowledge hub for the management of ground related risks that allow engineers to solve engineering problems, aid engineering decision-making, and identify project opportunities (Baynes et al., 2020). The benefits of a fully integrated GM-BIM approach have been successfully demonstrated by recent projects adopting a BIM-based and data-driven ground modelling, such as Crossrail 2 in London (Ting et al., 2020). For projects such as these, the 3D ground model acts as the engine to integrate and accumulate ground knowledge throughout all project stages in a 3D geological modelling environment (Figure 2). Through iterative modelling, the model continually evolves with an increasing degree of certainty and the aid of 3D visualization (Ting et al., 2020). The ground model is also a vital mechanism for contractors to understand what ground risks can reasonably be foreseen before construction commences (Baynes et al., 2020). Hence, it is recommended to incorporate the ground model in the project management system, from procurement to decommissioning (Harding, 2004; Parry et al., 2014; Baynes et al., 2020), to minimise contractual risks from claims for unforeseen ground conditions (Baynes et al., 2020).

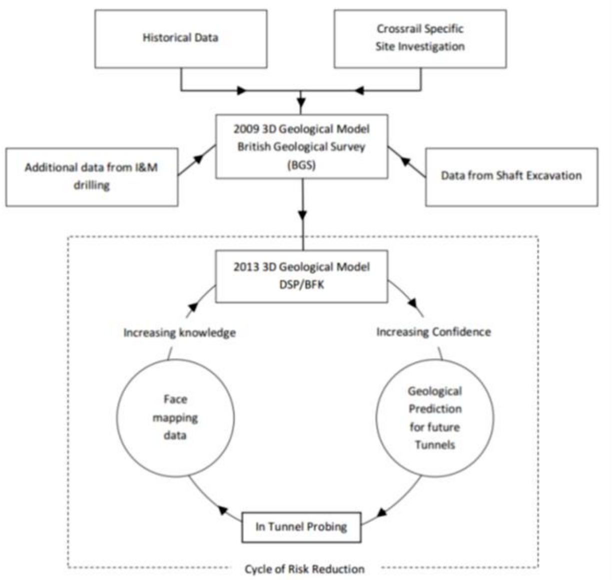

Figure 2: The cycle of risk reduction (adapted from Gakis et al., 2014)

2.3 Adopting BIM-Based Information Management Processes

Although a number of workflows for ground modelling have been proposed over decades, whole-life ground risk management has been challenging due to the aforementioned issues of ground information transfer. This section highlights the interconnection between BIM (Figure 1) and GIM (an example is presented in Figure 3) needed to achieve whole-life ground risk management. These workflows indicate that ground models are the backbone for the assessment of ground risks and decreasing uncertainty as a project progresses (GEO, 2007 and Gilder et al., 2020). Recently, Baynes et al. (2020) has defined a new workflow for ground risk management in civil engineering based on the IAEG Commission 25 Report (Figure 3). By comparing the BIM and examples of GIM, the interconnectivity between BIM and GIM are summarized as follows:

- Ground modelling is initiated with a review of existing relevant asset information during desk study.
- Within Project Information Management (PIM), ground model, data and information are generated (i.e. information production) from various stages, which includes documentation (technical reports), non-graphical information (geotechnical parameters, etc.), and graphical information (ground model).
- Discrepancies between the predicted ground model and new ground information act as the trigger events during the delivery and operational phases to refine the ground model. Further ground information may appear in all stages, including the construction phase and post-construction ground monitoring.
- In the operation or maintenance stage, the ground model may enter a repository of Asset Information Management (AIM), where it is continuously assessed and updated, if necessary.
- PIM and AIM may be managed within CDE.

This contrasts with the BIM uses of ground information suggested in the BIM standards, which is limited to the feasibility and design stages only.

2.4 Adopting BIM-based Ground Asset Management

Key to incorporation of geotechnical data within BIM for whole-life ground risk management is treatment of geotechnical data as an asset for decision-making in future projects (Antoljak, 2015; Kessler et al., 2015). Managing data in a data respiratory requires well-structured, reusable and interoperable data (Antoljak, 2015; Daly et al., 2019). This provides room for the transfer of ground information amongst different asset environments. This concept is currently adopted by Highways England using the Highways Agency Geotechnical Data Management System (HAGDMS). The system is an open web-based enterprise-level database for i) reusing geotechnical data and ii) facilitating informed decisions based on risk-based documentation and prioritization (Daly et al., 2019). Such usage demonstrates the benefits of structured, fragmented, and open data as valuable information for risk analysis which complies with the BIM principles.

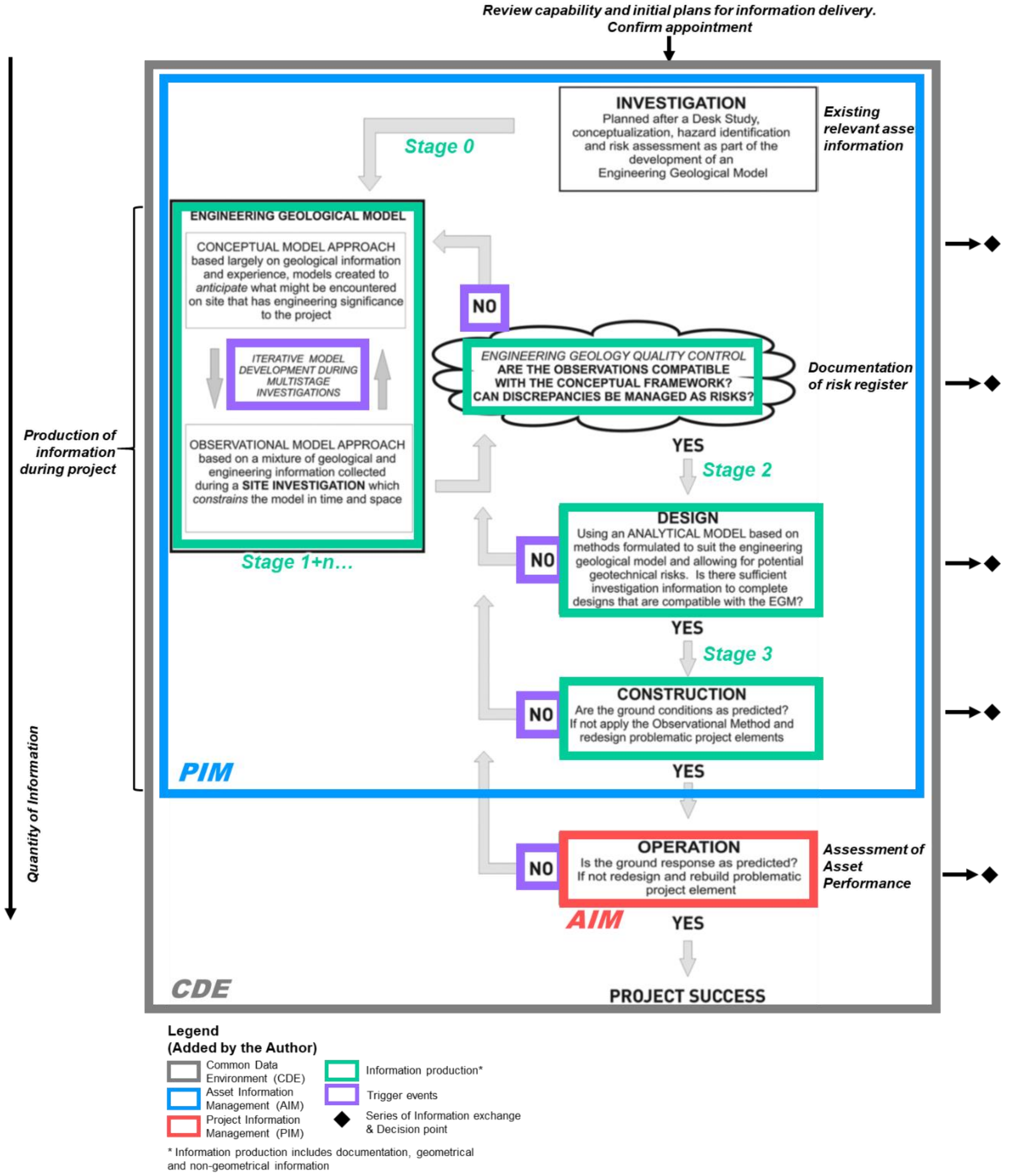

Figure 3: Workflow of using EGM for decision-making and risk management and its relationship with the BIM approach. Modified from Baynes et al. (2020).

3 Proposed BIM-based GIM for Ground Risk Knowledge and Uncertainty Transfer

3.1 Introduction

An information requirement-driven management system for ground information and knowledge (GKIM) is proposed to elevate the transfer of the data-information-knowledge (D-I-K) model for the ground within the BIM ecosystem in a digital and structured manner. A suggested framework of an IR-driven GKIM is illustrated in Figure 9. This covers the Business Layer, Standard Layer, and Information Layer of the Project Information Model (PIM) and Asset Information Model (AIM). AIM represents a national ground data repository that feeds the PIM throughout a project life cycle, and is fed back to by the PIM at the project close-out. Since it is unrealistic to formulate a global or national standard that caters for all disciplines, the following suggestions were considered when formulating discipline- or corporate-specific BIM standards, local BIM annexes, and IRs.

3.2 Business Layer – Information Requirements (IRs)

IRs, including Organisational Information Requirements (OIR), Project Information Requirements (PIR), Exchange Information Requirements (EIR), and Asset Information Requirements (AIR), act as the drivers of GIM to facilitate the maintenance of the ground model and procure high-value ground risk data and information. Tang et al. (2019) stressed the importance of a proper procurement of IRs to maximize knowledge reuse and minimize the construction cost due to fragmented information. As illustrated in Figure **4**4, IRs drive a cross-industry integration of digital twin (Tang et al., 2019) for the development of smart city.

The CIC BIM Adoption Survey 2020 concluded that 'Hong Kong client requirements' and 'Government policy' are the top BIM motivations (CIC, 2021). Given this, the recommendations herein are for the formulation of Project Information Protocol and National Geotechnical BIM-AM Standard as references for organizations to customize their IRs that fit national and organizational maintenance of the ground model.

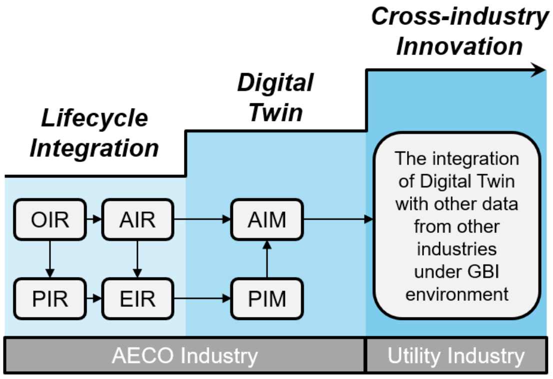

Figure 4: The impact of ISO19650 on the HK AECO Industry (Tang et al., 2019)

3.3 Standard Layer – Open Formats

Currently, the GIM is served as a standalone tool for the geotechnical expert due to its incompatibility with BIM formats and modelling methods. However, knowledge of ground data is essential during the initial design stage for both engineers and architects, meaning that GIM and BIM should not be independent aspects. The flow of data between GIM and BIM can be integrated for better collaboration through the use of OpenBIM formats (e.g. IFC), OpenGIS formats (e.g. CityGML), and BIM-GIS CDE platforms (Herlé et al., 2020). In this system, GIM can be linked to the native BIM platform to maximize the data sharing among all parties during the design stage. For instance, structural engineers may better understand the ground conditions and thus optimize their basement design when using a single source of information (CDE). The proposed information exchange and BIM-GIS integration are presented below.

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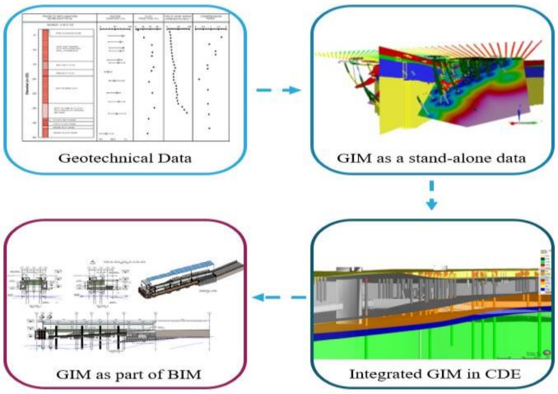


Figure 5: Integration of GIM and BIM through CDE

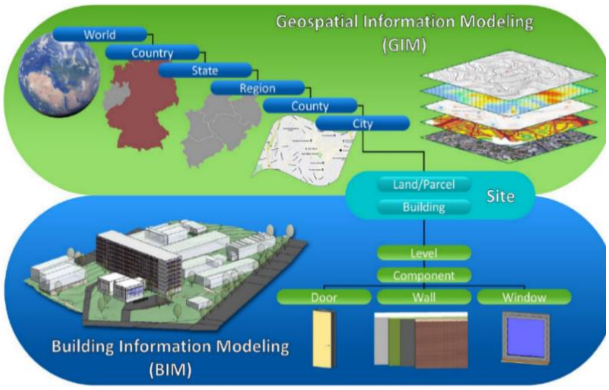


Figure 6: Information Exchange within BIM-GIS Integration

Storing a territory-wide GIM and BIM data in the form of OpenBIM format with standardized structures is the milestone towards developing automation in ground modelling and evaluation for urban planning.

3.4 Standard Layer – National-/ Project-specific Classification Systems

The classification system is the backbone needed to structure data and ease data extraction in the future. OmniClass and GEO's BIM Project Execution Plan Template present current requirements for geotechnical information, particularly the physical assets for foundation and excavation lateral support (ELS). This includes the ground information (Table 36: Information of OmniClass), geotechnical characteristics of the ground (Table 49: Properties of OmniClass), and geological model (CAT codes given by GEO's template). However, these are not available within ISO 12006-2:2020 and Uniformat. They are fundamental information for ground risk assessments and design and hence should be adhered to geometrical data for the downstream construction and operation.

However, the ground information and risks of concern to design engineers can be highly variable depending on the nature of the proposed works and ground characteristics. It is thus recommended to formulate a national classification system for geotechnical parameters and geological strata that comply with the local practice and standards of design and construction. Although GEO suggests some CAT codes for geotechnical projects in Hong Kong, it is impractical to cover all materials that would impact the geotechnical works. Therefore, in an early stage, the project engineering geologists should review the classifications of geological units and formulate a project-specific classification, if necessary.

3.5 Standard Layer – Project-specific Level of Information Needed (LOIN)

The LOD specifications by BIMForum, CIC, and GEO include geotechnical structures and the interacting geological strata (i.e., the profiles of bearing strata and rockhead), without stressing their intrinsic characteristics. According to BIMForum (2019), geotechnical regions are shown for context and not required to be modelled as part of this element at most LOD. However, this information is essential for geotechnical designs and construction. A project-specific LOIN should be established to fit the project needs, rather than adopting LOD as described in some of the standards. For instance, a reclamation site would require a preliminary model on the thickness and locality of soft clay to assess the risk of settlement in feasibility or design phases. In this case, low LOD suggested in the BIM standards would not be sufficient for preliminary study.

To transfer the ground knowledge and uncertainty through BIM, it is proposed to include the 1) raw data, 2) proceeded (standardized) data, and 3) interpreted data as the LOIN, where the interpreted data includes the delivery of the level of certainty (LOC) (See Section 3.5.1) and ground risk (See Section 3.5.2).

3.5.1 Level of Certainty (LOC)

While there has been a long history of quantitative and qualitative studies relating to ground model uncertainty, this paper focuses on a simple solution for a BIM-based transfer of semantic and geometric model uncertainty. This provides auxiliary information for model users to be aware and comprehends the uncertainty inherent in the ground model. The framework comprises geometric information (LOD-G), non-geometric information (LOD-I and metadata), and reports (DOC).

Digitalization of Knowledge

Ground knowledge is usually inherent implicitly in the ground model, making it hard to locate the uncertainty from subjective judgements. Modellers' interpretations and assumptions should be digitized and separately stored as explicit geometries (polylines, points, or meshes) or information (numbers or notes), which are then holistically modelled with the raw data (Mak et al., 2019). The digitized knowledge can then be transferred to the downstream project stages as LOD-G and LOC-I for model users and operators to visualize and reuse.

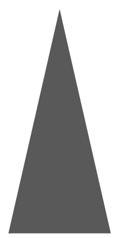
To maximize the value of information and avail the reuse of information, open or common formats should be used. This promotes compatibility with end-users' software programme or devices and aid to extract the right information at an appropriate time by the right person.

Type of Engineering Geological Model

The ground model is often taken as an absolute truth by engineers and stakeholders. It is imperative to convey to model users that every ground model is just an approximation of the ground conditions at varying scales (Baynes et al., 2020; Parry et al., 2014). Indeed, the concept of LOD in BIM is an analogue of LOC that presents uncertainty geometrically and semantically.

To convey ground-related uncertainty, the types of geological engineering model defined by IAEG Commission 25 can be adopted to represent the LOC of a model developed at different stages of a project (Figure 3 and Table 1) (Parry et al., 2014; Baynes et al., 2020). Being one of the most widely accepted standards for ground models, this can be a universal indicator of the uncertainty of a ground model stored as metadata.

Table 1. Types of EG Model for LOC

Type of EG Model*	Description*	Level of Certainty
Conceptual Model	Anticipation based on geological information from knowledge, experience, and relevant references	
Observational Model	A model refined from conceptual model based on the surface or sub-surface observations and measurements of geological and engineering information	
Analytical Model	A model refined from observational model for engineering analysis on ground behaviour	

* Development stage models defined by IAEG Commission 25 (Parry et al., 2014)

Auxiliary Information of LOC

Some of the model information can reflect the LOC to a certain extent, namely 'auxiliary information of LOC'. Access to this information through metadata or parameters of the model provides a cost-effective and straightforward way to indirectly enhance model users' understanding of LOC. Examples of the auxiliary information of LOC are provided in Table 2. They may also be the indicators of evaluating the value of information for ground information managers to control the cost of data storage.

Table 2. Examples of Auxiliary Information of LOC

Auxiliary Information of LOC	**Description**	**Example**	
Project Stage	Stage of the project when the ground model was formed	• Feasibility Stage • Investigation Stage	• Design & Construction Stage • Post-construction Stage
Modelling Use	Usage of modelling aligning with BIM uses. For Engineering Analysis, type of geotechnical work should be provided	• Refer to BIM standards for BIM uses • Driven pile design	
Resolution or Scale	Resolution or scale of the ground model	• 10m	• 1:5,000
Development Stage of the Ground Model	See Section "Type of Engineering Geological Model" above	• Conceptual Model • Observational Model	• Analytical Model
Type of Knowledge	Type of interpreted data, linked with the corresponding digitized user knowledge. See Section "Type of Engineering Geological Model" above	• Hypothesized	➢ Assumptions based on experience only without technical support
		• Interpreted	➢ Interpretations based on the available information (i.e. maps, reports)
		• Observed	➢ Direct observations (i.e. mapping, intrusive ground investigation)

3.5.2 Ground Risk Registry

For BIM-based knowledge management of ground risks, it is proposed to establish a digital risk registry that links the geometrical information (e.g. locality of hazardous ground materials) and non-geometrical information (e.g. the type of ground hazards and their risks to the proposed engineering works). Communication of ground risk is recommended by Baynes et al. (2020) to present the locations where geology could adversely influence engineering using a graph (Figure 7) and risk register table. Applying the same concept in BIM, the graph can be stored as 3D BIM models [LOD-

Graphical (LOD-G)] which are "tagged" with the risk register table stored as metadata [LOD-Information (LOD-I)] and technical reports as [Documentation (DOC)]. The 3D geometries are essential for clash detection, considering the spatial relationship between hazardous ground materials (i.e. corestones) and proposed works (i.e. driven pile foundation) as a 'clash' in construction to minimize rework. Utilising CDE technologies, GKIM serves as a ground risk knowledge tracker for risk identification and categorization through knowledge query, and ground risk database for hazard assessment, mitigation design and performance monitoring (Figure9).

INSPIRE Data Theme: Natural Risk Zones by European Commission could be adopted in data specification. Metadata tagging should be enabled to query ground risk information and incorporate ground risks in 4D and 5D BIM modelling for procurement of on-site mitigation materials.

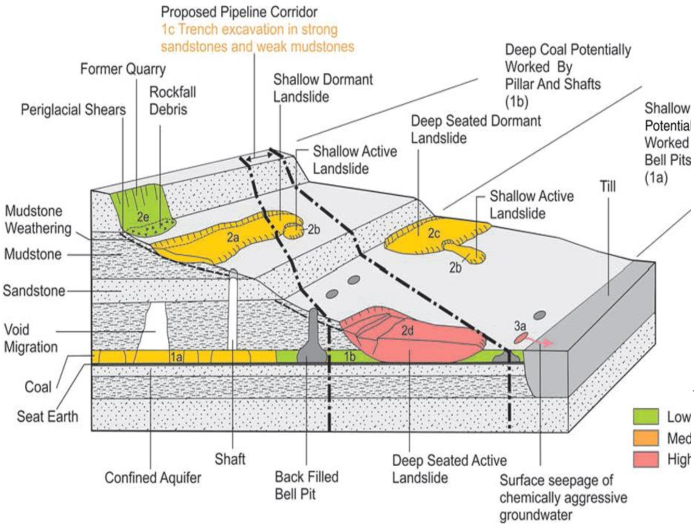


Figure 7: Visualization of Baildon engineering geological model used to communicate the qualitative risk assessment. (adapted from Baynes et al., 2020)

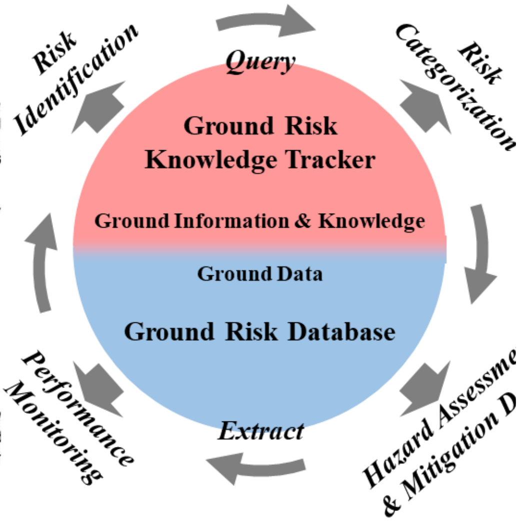


Figure 8: Ground Risk Management Process through GKIM

3.6 Feedback & Improvement

Continuous communication is critical in any projects for continual improvement of the BIM-AM standards and information requirements. This should be done among stakeholders, mainly the government, ground information management managers, project geologists, and the end-users of the ground model to maintain the information quality and effectively of information transfer within the ecosystem.

4 Ways Forward

To enable the digital transfer of ground models and interpreted data, a beta version of the schema extension 'AGSi' has been launched by a sub-group AGS DMWG in November 2020 (Chadwick et al., 2019). It adopts an object model-based schema to which fits GIS and BIM like IFC and OGC standards. The draft schema carries simple geometrical elements and linked attributes, including reporting. Coincidently, IDBE, a collaborative group between buildingSMART and OGC, is also developing a conceptual schema for ground models within the IFC and OGC standards. The recent emergence of a cloud-based collaborative platform for geotechnical data management like OpenGround also allows cloud-based integration with databases like gINT and HoleBase.

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However, the development of a BIM-complicit software is crucial to achieving the integration of GIM and BIM. Overall, there is a pressing need in the Technical Layer – i) ISO-compliant integrated asset information system designated for supplementing the existing BIM software deficiencies in standard compliance and ii) open format for the ground model, and Standard layer – iii) formulation of a BIM-based GIM through IR. Furthermore, there is a lack of guidance or methodology on evaluating the information being retained. A method for information evaluation would be critical in the digital future to avoid overloading low-value information and maintaining the quality of information (Tang et al., 2010).

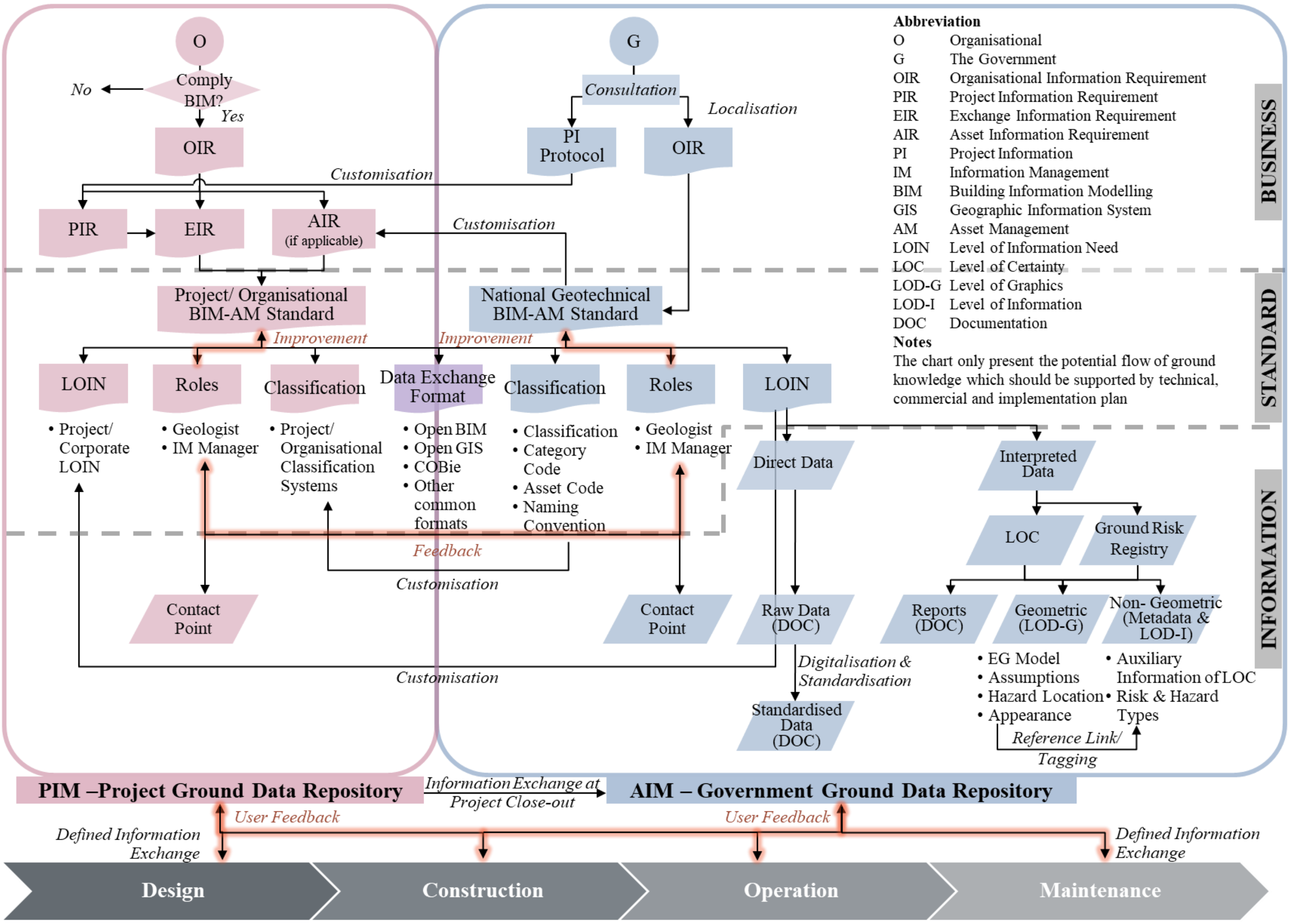

Figure 9: Proposed Framework of Information Requirement-Driven Ground Knowledge and Information Management

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