A BIM-Integrated Ground Modelling Approach for Fast-Paced Infrastructure Projects: A Case Study from Siu Ho Wan Depot Property Development

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ABSTRACT

For every project dealing with the ground, a ground model is necessary. Engineering Geological Models (EGM) help in understanding the risks associated with the ground and ensure the smooth delivery of the project, without encountering excessive unfavourable ground conditions that could affect the cost and progress.

When constructing ground models, the 2D traditional approach using GIS platform plus Surfer and Bentley gINT / Bentley holeBASE / Seequent OpenGround necessitates manual determination of the cross-cutting relationships among strata. The subjective nature of human interpretation may jeopardise the reliability and consistency of the interpretations across 2D geological sections. Moreover, limited visualisations and objectivity can also be issues with only 2D representations. Additionally, frequent reinterpretations are necessary when new data becomes available, which cannot meet the needs of fast-paced infrastructure projects.

To address these concerns, a new BIM-integrated 3D ground modelling approach is proposed. The available ground data have been synthesised to develop a preliminary 3D ground model with the aid of Seequent Leapfrog. This model identifies zones with specific concerns and key areas that require additional ground investigation works to address uncertainty in the ground. The workflow in the Seequent Leapfrog software allows for dynamic updates, progressively reducing uncertainty and generating a final resultant ground model. The 3D model also provides an excellent platform for visualising the complex stratigraphic sequence, testing assumptions, streamlining design drawing production, and aiding in the interpretation of site-specific ground conditions. It also offers high interoperability with other common BIM software packages, facilitating design integration and promoting cross-disciplinary communication, which is particularly important for mega-scale projects.

This paper discusses the BIM-integrated 3D ground modelling approach employed for the total engineering design of the MTRC Siu Ho Wan Depot Phase 1 Development and Oyster Bay Station Project, highlighting the benefits of this integrated modelling approach provided.

KEYWORDS: Leapfrog, Ground Model, Engineering Geological Model, BIM Integration

1. Introduction

The ground is inherently complex as it has been shaped by intricate geological processes throughout geological time. Ground models serve as fundamental representations of subsurface conditions, and their significance lies in their ability to provide a 3D understanding of lithology, stratigraphic sequences, structural geology, geological processes, geomorphology, and more, depending on specific needs. Developing ground models requires geologists to translate, interpret, and integrate information from various sources, including desk studies, field observations, laboratory experiments, intrusive ground investigations, remote sensing, and geophysics, among others. The model development process involves establishing conceptual models based on the knowledge and experience of geologists, which then evolve into observational models (Baynes & Parry, 2022).

For every infrastructure project, it is essential to establish an EGM to understand the geological setting, provide spatial distribution of different types of materials, and make essential data available for design and informed decision-making. EGM further facilitates the evaluation of how these ground conditions interact with the proposed project elements. EGM also acts as a de-risking tool by identifying geological and geotechnical risks and predicting high-risk areas, enabling better preparedness and reducing the occurrence of unforeseen ground conditions that could potentially disrupt construction works. This is of paramount importance, particularly considering that the integrity of the design must be maintained, while the increasing complexity and forms of structures are pushing the boundaries of design.

2. Modelling Data for Infrastructure Projects

Infrastructure projects typically require geological data with high certainty and little ambiguity. In addition to desk studies, which involve examining geological maps, interpreting aerial photographs, and reviewing information from previous projects in the vicinity, field observations and intrusive ground investigation works are essential sources of data for the EGM. These investigations often involve drilling boreholes and excavating trial pits using appropriate sampling methods. Field and laboratory tests are conducted to complement the data obtained.

During the ground investigation process, the lithology at different depths is thoroughly described in the ground investigation logs. Field tests such as standard penetration tests, vane shear tests, and permeability tests provide indications of soil stiffness, strength, and permeability. Televiewer surveys are conducted to obtain orientation data on rock discontinuities, which are essential for assessing the rock mass. In combination with laboratory test results, these investigations help in understanding the mechanical behaviours and characteristics of different soil and rock materials, which are crucial for design purposes.

The data obtained from intrusive ground investigations, along with other sources, play a vital role in reducing uncertainties and providing a solid foundation for informed decision-making in infrastructure projects.

3. Modelling Approaches

The major steps in ground model development include simplifying ground data for project-specific uses, establishing a ground data management system, constructing surfaces representing geological boundaries, and determining the stratigraphic sequence. These processes can be iterative when ground data becomes available in stages.

Figure 1 presents the generic workflow commonly adopted in Hong Kong for developing the EGM using both the 2D traditional approach and new BIM-integrated approach. The workflow outlines the simplified procedures from digesting raw data and compiling modelling information to developing preliminary and refined EGM.

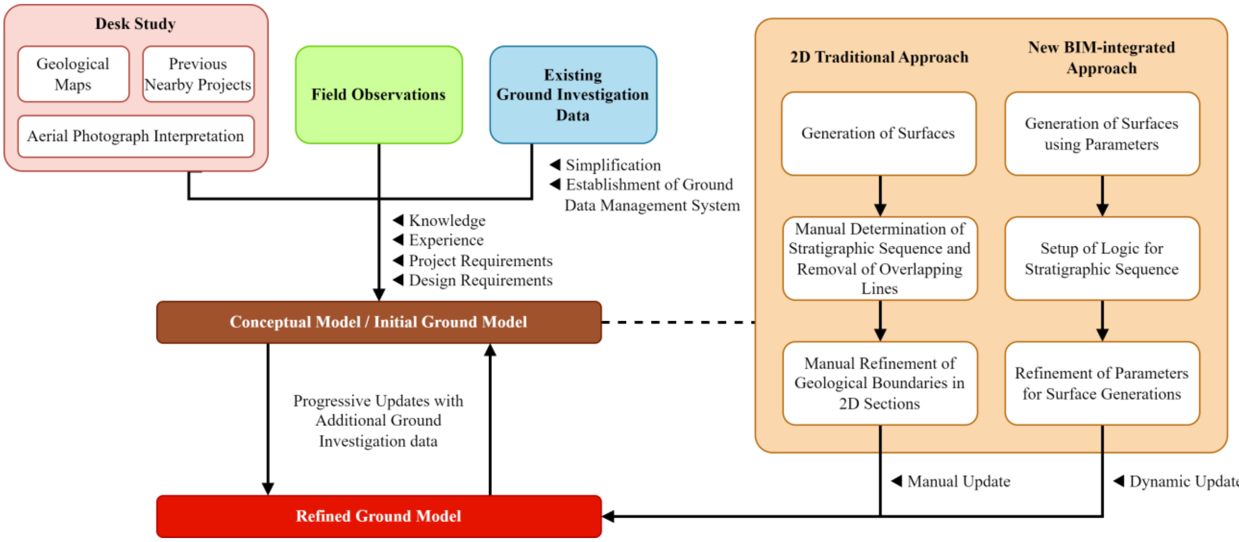

Figure 1. Hong Kong's Generic Workflow for Developing EGM

3.1 Ground Data Management

Irrespective of whether the traditional or new BIM-integrated approach is used for developing the EGM, it is crucial to establish a database for ground model management that incorporates the interpreted geological data from raw information. The ground investigation logs contain objective and descriptive information about the lithology, including approximate strength, colour, texture, grain size, weathering grade, soil/rock type, and more. To make the raw geological data more suitable for input into the EGM and presentable in block models and geological sections, the lithology is typically simplified to the level required by the project.

In addition to the lithology information, the ground investigation logs also provide details such as locations, depths, orientation, and other relevant data. These data are unified and stored in a ground data management system using commercial software packages like Bentley gINT, Bentley holeBASE, or Seequent OpenGround. These software packages serve as tools for managing and organising the ground data, allowing for efficient storage, retrieval, and analysis of the information.

3.2.1 2D Traditional Approach

The traditional modelling approach for developing the EGM relies heavily on 2D geological sections. In this approach, interpolated surfaces are converted into 2D representations, and the relative ages and cross-cutting relationships of different strata are examined. The geological boundaries are manually refined to remove any peculiar geometry. However, this process of generating geological sections is time-consuming, and the entire production cycle needs to be repeated when new data becomes available.

By simplifying a 3D problem into a 2D presentation, there is inevitably a loss of consistency and reliability across different geological sections. The series of geological sections also offer limited objectification and visualisation of the overall geological condition. The manual determination of stratigraphic sequences and subsequent refinement introduce a high degree of subjectivity, making the EGM non-reproducible. This subjectivity becomes even more problematic when dealing with complex geology that includes intrusions, soil lenses, cavities, and geological structures. Additionally, documenting the subjective modifications becomes nearly impossible, and subjectivity can easily accumulate as the EGM evolves.

3.2.2 New BIM-integrated Approach

The new BIM-integrated approach utilises commercial software packages like Seequent Leapfrog to construct the EGM in a 3D manner. This approach ensures the integrity and spatial consistency of the EGM. A logical framework can be applied to establish the sequences of different strata. The interpolation of surfaces and construction of intrusion bodies and lenses are parametrically controlled, providing users with a high degree of manipulation and flexibility. This enhances the objectivity of the EGM and makes them reproducible by different users when the modelling parameters are well documented. Additionally, when new data becomes available, the EGM can be easily and dynamically updated using the same logical framework and set of modelling parameters.

The design BIM can be integrated into the EGM for understanding the spatial relationship and interaction between the proposed works and the ground materials. The visual capabilities and easy interrogation of a 3D EGM enable the identification of areas with significant information gaps and potential adverse ground conditions. This eases the proposal of additional ground investigation works to validate these areas further. Examples of such conditions could include abrupt changes in rockhead contour, abnormally thick corestone layers, or the presence of geological structures. This approach greatly facilitates the progressive refinement of the initial model into a well-established resultant model, providing sufficient information for design purposes and compliance with statutory requirements.

4. Case Study: Siu Ho Wan Depot Phase 1 Development and Oyster Bay Station Project

4.1 Background and Site Setting

In May 2021, the MTR Corporation Limited commissioned Arup to provide a total engineering solution for the Siu Ho Wan Depot Phase 1 Development and Oyster Bay Station Project detailed design under Consultancy Agreement No. C1701. In the project, a 30-hectare reclaimed land along the northern shoreline of Lantau Island in Hong Kong is being reprovisioned for an operating depot and supporting railway facilities, along with road works connecting to the surrounding area. The site, which was previously reclaimed around 1993, measures approximately 1,600 meters in length and 230 meters in width. Arup's geotechnical team has been assigned the responsibility of designing the foundation, excavation and lateral support, and site formation works. The team is also conducting detailed geological and geotechnical assessments, including studying the site's history, characterising the ground conditions, interpreting laboratory test results, and identifying key geological and geotechnical constraints.

The ground investigation works for this project were conducted in stages, and Arup was involved in proposing the final stage of investigations. Following the project commissioning, a desk study, aerial photograph interpretation, and the development of an initial ground model were carried out. This initial ground model has been utilised to identify locations where additional ground investigation works are required.

4.2 Development History

As revealed from the aerial photographs in **Figure 2**, the site was predominantly an offshore area to the north of Lantau Island with the exception of the pre-existing headland located in the central landward portion of the site. The site remained largely unmodified until reclamation works began in 1993, which were completed in 1994. As part of the reclamation, the pre-existing headland was removed, resulting in the formation of several cut slopes nearby. Construction activities for the existing depot, North Lantau Expressway, Tung Chung Line, and Airport Express Line commenced in 1995 immediately after the reclamation works and were completed in 1997/98. There have been no significant changes within or in the vicinity of the site, apart from the construction of the Tuen Mun – Chek Lap Kok Link to the southwest of the site between 2014 and 2017.

During the reclamation process, both dredged and undredged methods were utilised. The dredged method was primarily employed for the footprint of the main depot building in the central seaward portion of the site, while the undredged approach was adopted for the rest of the area.

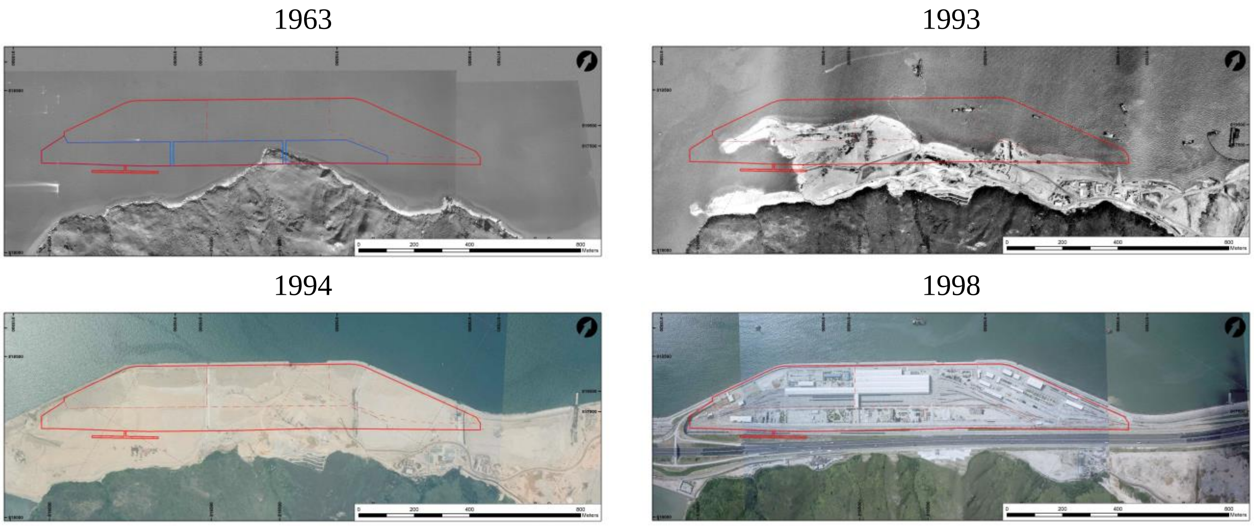

Figure 2. Aerial Photographs of the Site

4.3 Geological Setting

Based on the available ground investigation data, the stratigraphy of the site consists of several layers. The topmost layer is reclamation fill, which was used during the reclamation process. Below the fill layer, there is a layer of marine deposit, followed by alluvium. Within the lower portion of the fill layer or at the interface between the fill and marine deposit, localised pockets of disturbed marine deposit can be occasionally found. These pockets may indicate areas where the marine deposit has been affected or altered during the reclamation process.

Underlying the superficial deposits, the in-situ material consists mainly of feldsparphyric rhyolite or granite with varying degrees of weathering. The weathering grades can range from slightly weathered to completely weathered, depending on the specific location and depth.

There is also a zone of partially weathered rock mass, often referred to as corestones. These corestones are typically sandwiched between a layer of saprolitic soil (highly and completely weathered material) and a competent rock layer. Corestones are partially weathered rocks that have retained their integrity and strength compared to the surrounding weathered material.

The presence of fault-related materials is evident at the site. This includes fault gouge, fault breccia, slickensided joints (polished and grooved surfaces along fault planes), closely-spaced microfractures, brecciation and shear indicators. These observations suggest the presence of multiple faults that cut across the site.

4.4 Process of Model Development

In the Siu Ho Wan Depot Phase 1 Development and Oyster Bay Station Project, an initial ground model, as depicted in **Figure 3**, has been developed using information from the desk study, aerial photograph interpretations, and existing ground investigation data. The ground data have been processed into suitable formats for the Seequent Leapfrog software. Similar lithologies have been grouped together to remove inconsistencies in geological descriptions across different ground investigation episodes.

The purpose of the initial ground model is to provide a preliminary understanding of the ground conditions, identify information gaps, and pinpoint areas with significant geological risks. Notably, the location around the pre-existing headland exhibits a steeply dipping rockhead profile, and there are localised areas where the rockhead level drops suddenly, potentially indicating fault features. The undredged reclamation method used in the project has resulted in the presence of marine deposits and disturbed marine deposits as discrete pockets. These compressible soils raise concerns about excessive and differential settlement, but their extent and distribution have not been fully understood.

Based on these findings, a proposal for the final stage of ground investigation has been developed. The aim is to address information gaps, meet statutory requirements, provide sufficient design information, and fulfil the needs for environmental assessment. The density of ground investigation stations in the final stage will be adequate to achieve these objectives.

Leveraging the dynamic update capability of Seequent Leapfrog, the initial EGM can be progressively updated as information from the final stage of ground investigation becomes available in batches. The refined EGM, presented in **Figure 4**, reflects these updates. It provides a more accurate representation of the alluvium by differentiating it into fine-grained and coarse-grained units. The locations of marine deposit and disturbed marine deposits are also more precisely depicted. By examining the distribution of fault-related materials, areas with thickened corestone layers, and sudden drops in rockhead level, the presence of several faults has been inferred.

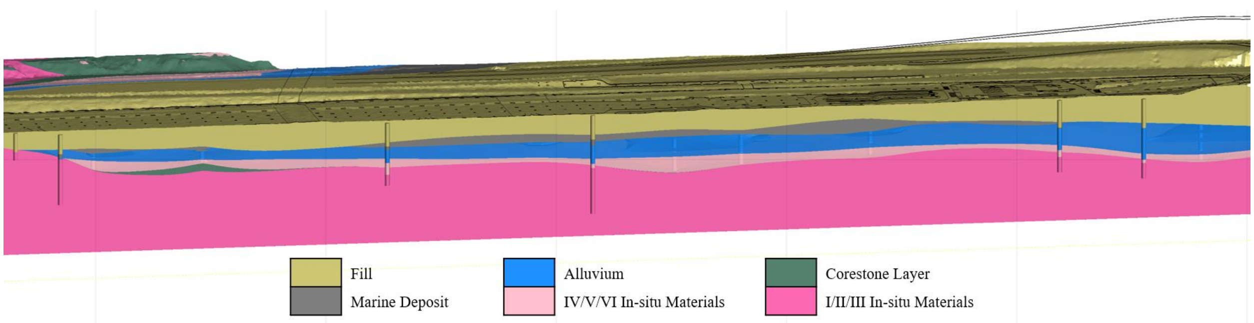

Figure 3. Initial Engineering Ground Model – Longitudinal Section

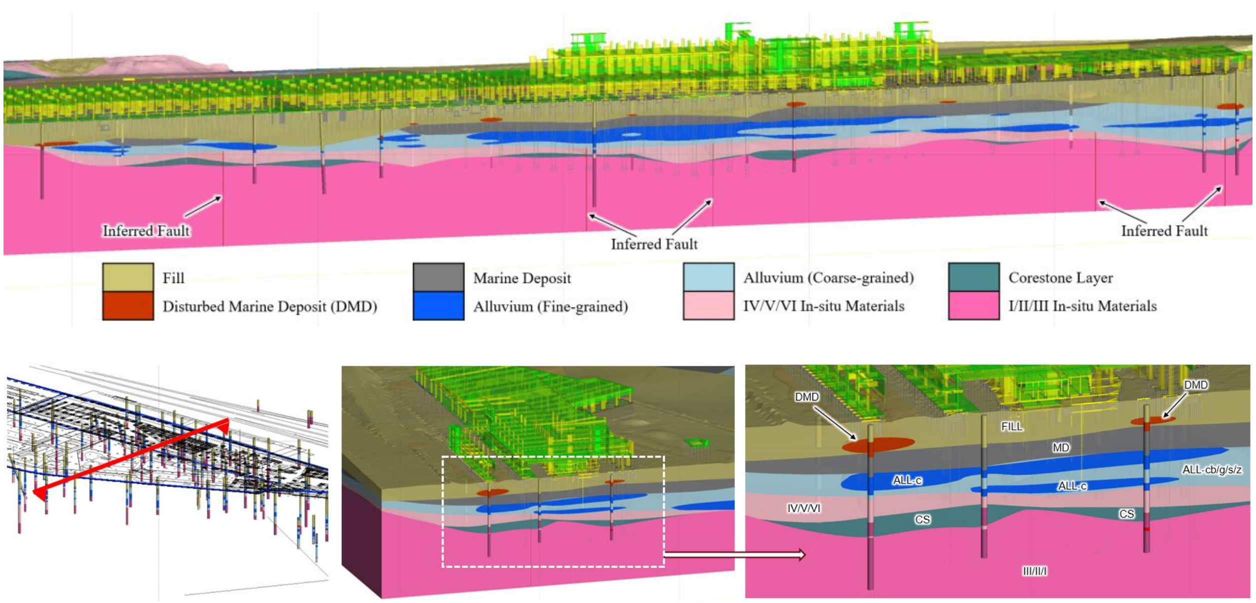

Figure 4. Refined Engineering Ground Model –
Longitudinal (Above) & Transverse (Below) Sections

To ensure the accuracy and geological correctness of the EGM, a thorough review of the model has been conducted. This review ensures that all geological intervals within the borehole data are accurately captured and examines whether further refinement of the modelling parameters is necessary.

4.5 BIM Integration and Geotechnical Baseline Report (GBR)

In the process of compiling the Geotechnical Baseline Report, it is crucial to quantify the construction materials involved. Traditionally, this quantification process can be complex and typically relies on critical 2D sections. However, with the integration of BIM into the EGM, the quantification of construction materials can be significantly streamlined.

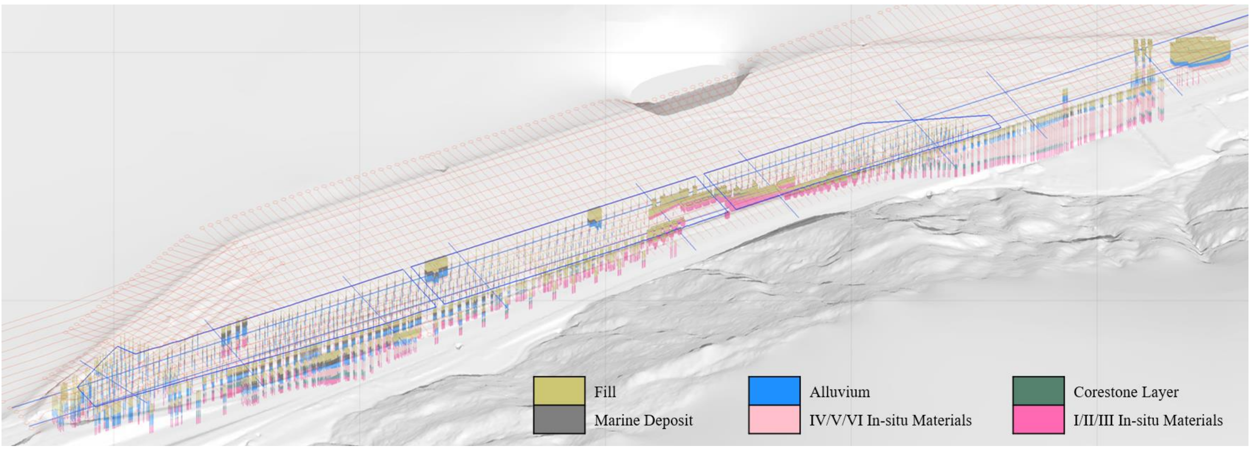

Figure 5. Assessment of Geological Units Encountered by Pile Foundations after BIM Integration

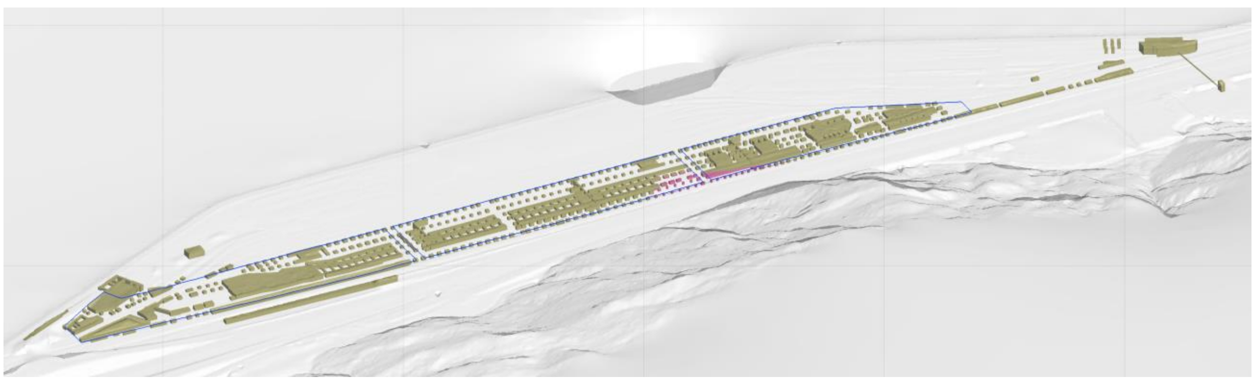

Figure 6. Assessment of Geological Units Encountered by Bulk Excavations after BIM Integration

The BIM integration allows for the superimposition of the design BIM with the EGM. By doing so, the materials within and outside the design BIM boundary can be defined, enabling a clear understanding of the volume of excavation and the nature of the excavated materials. The integration with the design BIM provides the advantage of accurately deducing the amount of construction materials, which can then be included in the Geotechnical Baseline Report. This integration enhances the reliability of the deduced volume and minimises design risks for the engineers involved. This can also potentially attract more realistic fee in the tender submission by the contractors and avoid unnecessary claims. **Figure 5** and **Figure 6** showcase different geological units encountered by the pile foundations and bulk excavations, respectively. These figures provide visual representations of the stratigraphy and geological conditions related to different type of design elements. Furthermore, the stratigraphy information within the EGM can be exported to a number of common BIM formats such as .ifc, .dwg, and .dgn. This enables the incorporation of the stratigraphy data into various BIM platforms, facilitating cross-disciplinary collaboration and communication among different stakeholders.

Benefiting from BIM integration and the 3D representation of the EGM, the quantification of construction materials becomes more efficient, accurate, and compatible with other disciplines involved in the project.

4.6 Geological Risk Identification

Within the EGM, several key geological constraints are evident. These constraints include:

1. Excessive or differential settlement: This is primarily contributed by fine-grained soils such as distributed marine deposit, marine clay, and alluvial clay. These types of soils are prone to settlement and can cause variations in the behaviour of the ground.

2. Boulder-sized hard materials: These hard materials are present within the fill, alluvium, and corestone layer. Their presence can pose challenges for the installation of pile foundations, as they may obstruct or impede the penetration of piles into the ground.

3. Presence of faults: The presence of faults within the site results in several geological effects. These effects include thickened corestone zones and varying rockhead levels. Faults can affect the stability and behaviour of the ground, and they need to be considered in the design and construction process.

By adopting the new BIM-integrated approach, these geological constraints can be effectively addressed. For example, the lenes of fine-grained soils can be parametrically modelled. This allows for a more accurate representation of the distribution and characteristics of these soils. Furthermore, the BIM-integrated approach enables the extraction of a list of pile foundations that are potentially affected by these fine-grained soil lenses. By analysing the outputs, engineers can quickly identify the pile foundations that intersect or are in close proximity to the areas influenced by fine-grained soils. This information helps in assessing the potential risks and designing appropriate mitigation measures for these affected pile foundations.

5. Conclusion

Engineering Geological Models (EGM) play a crucial role in infrastructure projects by providing an understanding of subsurface conditions. They are developed through the integration of various data sources, including desk studies, field observations, laboratory experiments, and ground investigations. The data obtained from ground investigations, such as drilling boreholes and conducting tests, help in reducing uncertainties and providing a solid foundation for decision-making.

There are two main approaches to EGM development, namely the traditional 2D approach and the new BIM-integrated approach. The traditional approach relies heavily on 2D geological sections and involves manual refinement, making it time-consuming and subjective. On the other hand, the new BIM-integrated approach utilises 3D modelling software, ensuring spatial consistency and objectivity. It allows for a logical framework for stratigraphic sequence and parametric control for surface generation, enhancing reproducibility and facilitating dynamic updates when new data becomes available. The integration of BIM into ground models offers several additional advantages. It facilitates the proposal of ground investigation works by clearly locating areas with insufficient information. It also streamlines the quantification of construction materials, allowing for accurate volume estimation and reducing design risks. BIM integration also enhances cross-disciplinary collaboration and communication among stakeholders by enabling the incorporation of stratigraphy data into various BIM platforms. These all are particularly useful for mega-scale projects like the Siu Ho Wan Depot Phase 1 Development and Oyster Bay Station Project which is complex, fast-paced, and multidisciplinary.

Geological risks, such as excessive settlement, boulder-sized hard materials, and faults, can be effectively addressed through the BIM-integrated approach given the spatial relationship between the design elements and the ground materials contributing to the geological risks is well understood. For instance, parametric modelling helps in accurately representing the distribution of fine-grained soils, and the identification of affected pile foundations allows for the assessment of risks and the design of appropriate mitigation measures.

Overall, the new BIM-integrated approach to ground modelling improves the consistency, objectivity, reproducibility, interoperability of models, leading to better informed decision-making, reduced risks, and improved design outcomes in infrastructure projects. The knowledge and experience of geologists should also be appreciated during the ground model development as these are always the key components when formulating the conceptual model, determining the stratigraphic sequence, and setting modelling parameters to ensure the resultant EGM is geologically reasonable.

References

Baynes, F. J., & Parry, S. (2022). Guidelines for the development and application of engineering geological models on projects. *International Association for Engineering Geology and the Environment (IAEG) Commission 25, Occasional Publication, 1*.