Development of Three-Dimensional Geotechnical Models for Territorial and Infrastructural Development in Hong Kong

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ABSTRACT

With an aim to support the Smart City Blueprint for Hong Kong, the Geotechnical Engineering Office (GEO) of Civil Engineering and Development Department (CEDD) has been taking a steering role in developing 3D geotechnical models (3DGM) for supporting territorial and infrastructural development in Hong Kong. In parallel to the recent revamp of the centralised data repository Geotechnical Information Infrastructure into a three-dimensional mapping system (namely 3DGInfo), the GEO has initiated a pilot study to develop territory-wide 3DGM utilising existing ground investigation (GI) records collected from public and private projects. Unlike conventional geological maps, the 3DGM is designed for practical engineering applications, such as giving reference to the optimal foundation depths for various types of deep foundations. By providing detailed insights into subsurface conditions, the 3DGM enables planners and engineers to efficiently assess site-specific geology and streamline decision-making during the early stages of development projects. A customised workflow was proved successful in generating 3DGM blocks in Wan Chai, Tung Chung East reclaimed land and a marble site in Yuen Long. Riding on the success of the pilot study, the GEO is working to further enhance the 3DGM generation methodology using state-of-the-art technologies and has prioritised a new phase of 3DGM block creation in the Northern Metropolis Development areas. This paper discusses the innovative solutions adopted and the GEO's vision and roadmap for developing territory-wide 3DGM to enhance GEO services and benefit practitioners.

1 INTRODUCTION

The GEO is always taking a steering role in the application of innovation and technology (I&T) for advancing geotechnical practice in Hong Kong (Cheung, 2006; Cheung, 2021; Shum et al., 2024). As part of the Government's mission to digitally transform the construction industry, including private development and public works, one of the initiatives is to convert raw data into actionable insights, i.e. moving from being data-rich to information-rich structure, to enhance the efficiency in the delivery of engineering projects.

In parallel to the evolution of the Geotechnical Information Infrastructure to a three-dimensional mapping system (3DGInfo), the GEO has initiated a pilot study to develop territory-wide subsurface ground models, namely the 3D Geotechnical Models (3DGM). This initiative aligns with the Hong Kong Smart City Blueprint, which will equip practitioners to rapidly assess subsurface conditions and streamline the decision-making on engineering applications for future projects. By harnessing decades of ground investigation (GI) records collected by the GEO, a subsurface spatial data inventory in a truly three-dimensional space is being established. The GEO envisions that the 3DGM will be the fundamental step to advance digitalisation and automation in the engineering sector, fostering widespread adoption of digital models and enabling the industry to unlock the full potential of modernised digital workflows.

2 PILOT THREE-DIMENSIONAL GEOTECHNICAL MODEL

To facilitate the understanding of the ground conditions in the early stages of engineering projects, the GEO developed 3DGM in designated pilot areas for trial uses in foundation studies. Unlike conventional

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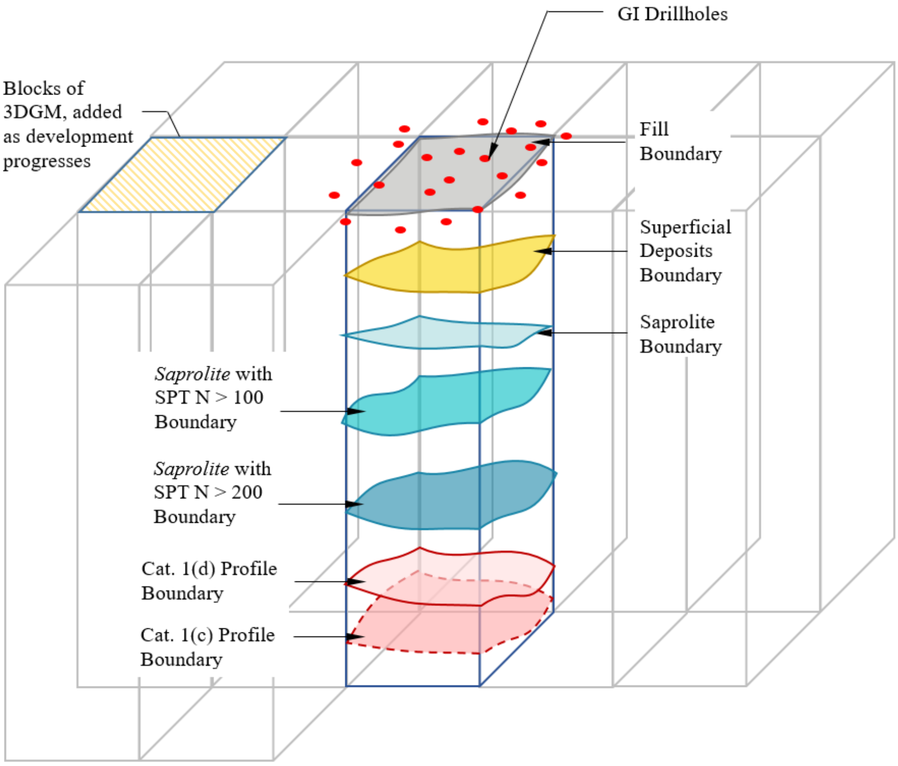
geological maps, the 3DGM emphasises its relevance to engineering applications. In the pilot study, stratigraphic interfaces are delineated with reference to typical foundation design practices in Hong Kong. For instance, steel-H piles are usually driven to refusal in soil stratum with Standard Penetration Test (SPT) N-value greater than 200, whereas end-bearing piles are founded on Category 1(d) and Category 1(c) rocks with specific presumed allowable bearing pressure. Figure 1 illustrates the stratigraphic interfaces adopted in the pilot 3DGM.



*Cat. 1(d) and Cat. 1(c) refers to Bedrocks Described in Table 2.1 of Code of Practice for Foundations (BD, 2017)

Figure 1: Stratigraphic interfaces in pilot 3DGM for typical foundation design in igneous rock

2.1 The Pilot 3DGM generation methodology

The pilot 3DGM generation methodology is developed based on the prevailing engineering practice to support foundation design in Hong Kong. The key procedures are shown in Figure 2 and summarised below:

1. **Data Collection:** Territory-wide air-borne LiDAR survey (for ground profile), borehole records.
2. **Data Extraction:** Extract relevant information (e.g., soil/rock type, SPT N-value, total core recovery and weathering grade of bedrock) and determine levels of relevant stratigraphic interfaces for foundation design (e.g. Cat. 1(c) level).
3. **Interpolation:** Generate contours of different stratigraphic interfaces using the linear triangulation method in commercial software.
4. **3D Model Generation:** Populate the volume between the contoured surfaces and the ground profile with voxels (3D pixels) in the network common data form (netCDF) format by using customised Python scripts and GIS software.

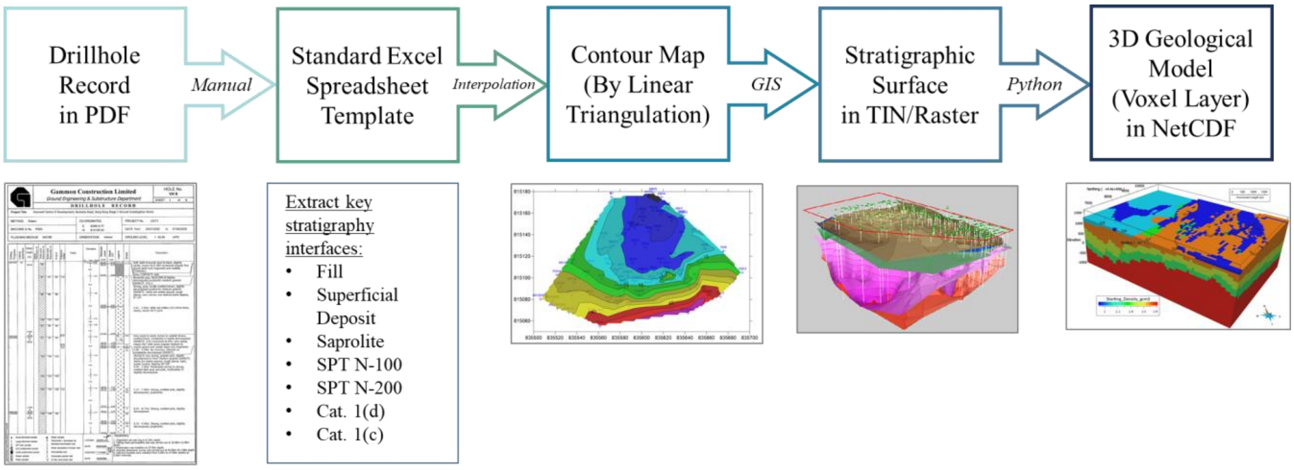


Figure 2: Existing pilot 3DGM generation methodology

By using the above generation methodology, the GEO created four pilot 3DGM blocks in Hopewell Centre II, Wan Chai urban area (Map Sheet No. 11SW-14B), Tung Chung East reclaimed land (Map Sheet No. 9SE-4B) and a marble site in Yuen Long. These pilot 3DGM blocks comprise voxel cells (each of 1 m cubic dimension) in grids (Figure 3). Voxels are small, cube-shaped units of volume that can be arranged in 3D space to represent objects of any size and shape. In recent years, voxel-based 3D modelling has gained popularity for representing complex and discrete volumetric objects. They are particularly well-suited for representing irregular and fragmented structures, such as terrain and geological formations.

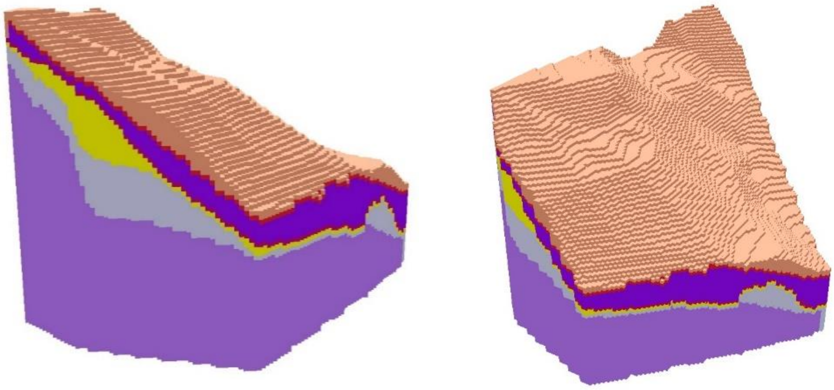


Figure 3: Pilot 3DGM in voxel format

Besides representing the 3DGM blocks in voxel format, the corresponding boreholes can be generated concurrently together as 3D sticks under the same process. Practitioners can display the 3D borehole sticks on top of the 3DGM blocks in 3DGInfo (Figure 4). The spatial distribution of the boreholes used could indicate the density of source data and qualitatively give a measure of reliability for the 3DGM generated. Practitioners should be cautious when using the pilot 3DGM in areas with limited borehole data. However, they can focus on adding GI boreholes in those areas with a lower density of existing boreholes to supplement the insufficiency of subsurface data.

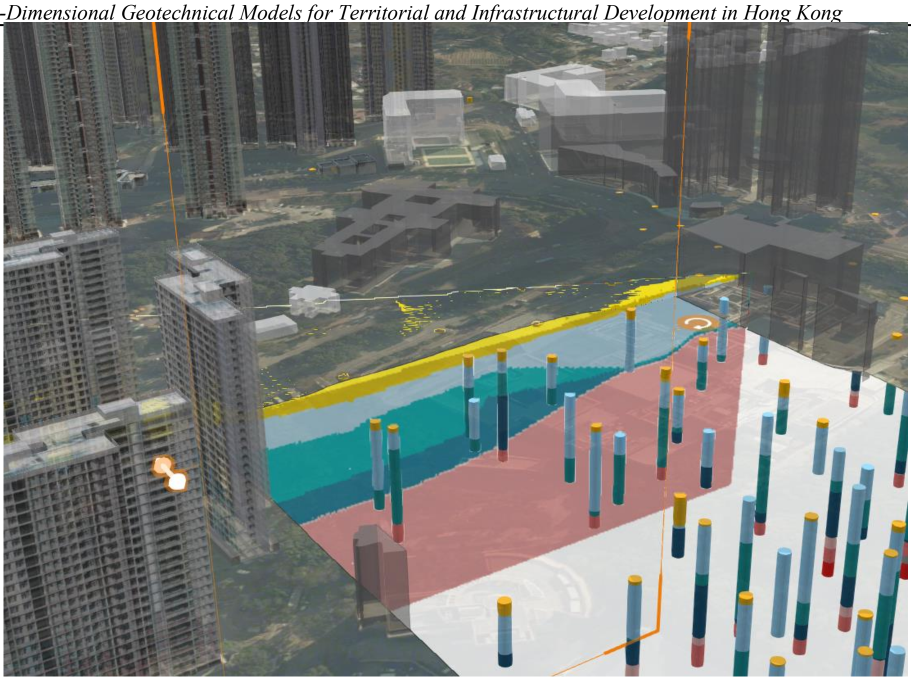


Figure 4: 3DGM overlaying with GI in 3DGInfo

2.2 Pilot 3DGM currently available in 3DGInfo

The first batch of pilot 3DGM blocks confirmed the feasibility of transforming conventional 2D contour maps into 3D models, which enable a rapid visualisation of regional subsurface conditions for foundation studies. Instead of creating project-specific models, the GEO targeted to progressively build up a city-scale subsurface spatial dataset by linking up multiple 3DGM blocks built in standard 1:5000 survey map sheet scale, i.e. a plan area of 750 m × 600 m for each block. This delineation method allows flexibility in phased development and future updating of individual blocks on a modular basis. Figure 5 shows the pilot 3DGM block in Wan Chai.

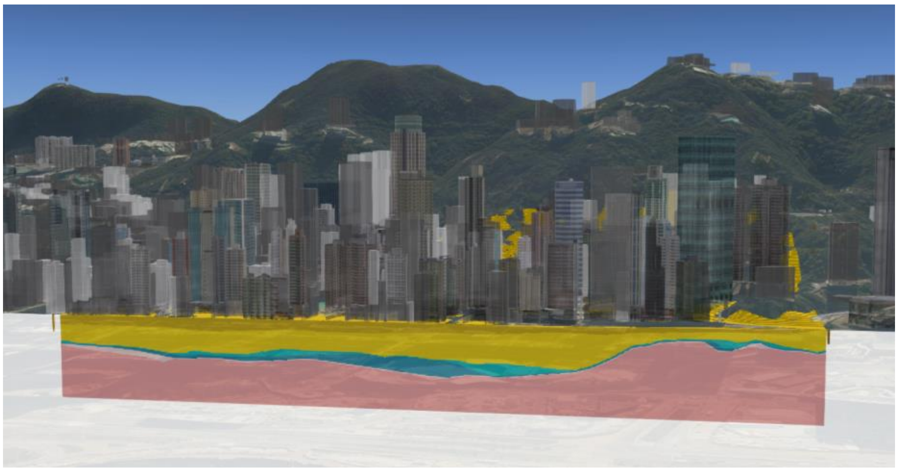
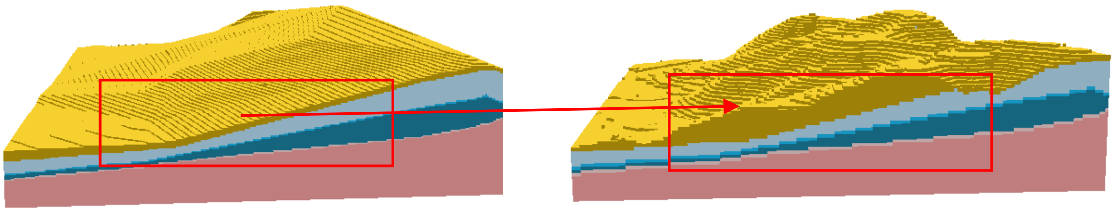


Figure 5: Pilot 3DGM block in Wan Chai (Map Sheet No. 11SW-14B)

2.3 Pilot 3DGM blocks facilitating Northern Metropolis Development

Building on the success of the in-house pilot study, the GEO engaged consultants with the objectives of tapping their expertise and knowledge to enhance the 3DGM generation methodology in ground modelling and accelerating the construction of the 3DGM to support upcoming new town developments in the Northern Metropolis Development Areas (NMDAs).

Study areas with different geological settings were selected to evaluate the applicability of the existing 3DGM workflow and identify areas for improvement. The enhanced generation methodology can now modify the ground profile based on 2020 LiDAR survey results (Figure 6), incorporate inferred rock contact and sub-vertical boundary change interpreted by experienced geologists (Figures 7 & 8) and attach in-situ field test results (such as SPT-N values and total core recovery) on 3D borehole sticks (Figure 9).



(a) Ground surface based on GI data

(b) Ground surface based on 2020 LiDAR results

Figure 6: Modification of 3DGM ground profile based on 2020 LiDAR survey results (AECOM, 2024)

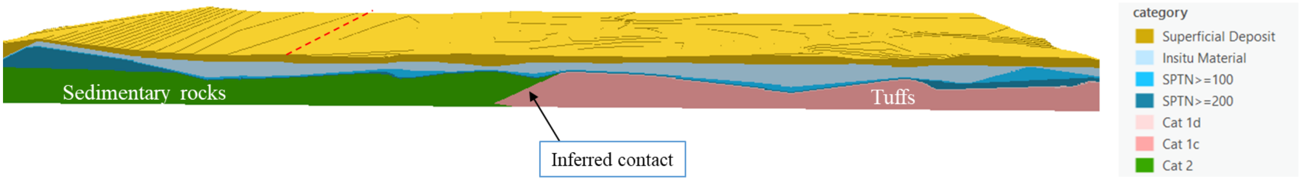


Figure 7: Modelling of inferred rock contact and sub-vertical boundary change (AECOM, 2024)

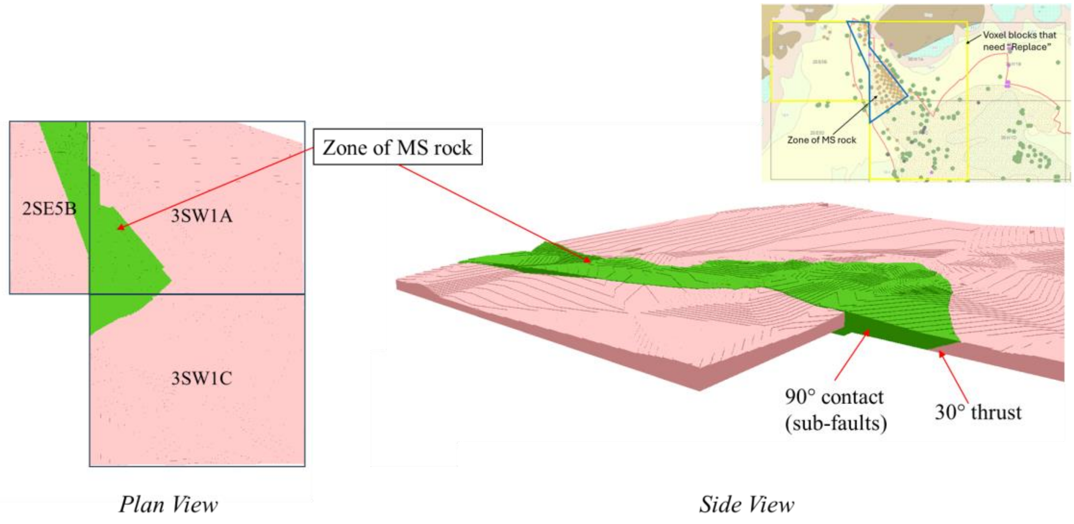
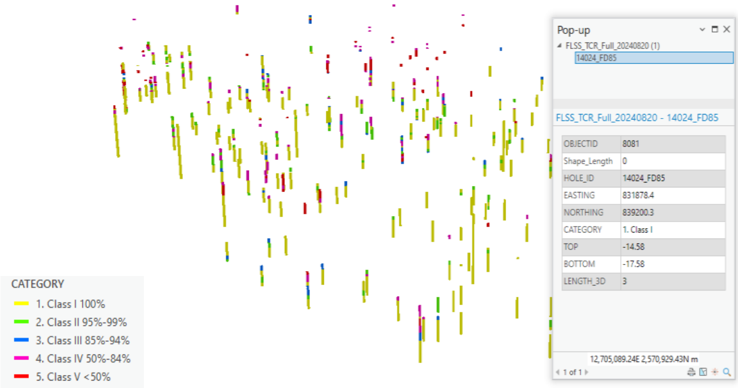


Figure 8: Modelling of different rock types within and across different 3DGM blocks (AECOM, 2024)



FLSS_TCR_Full_20240820 - 14024_FD85

OBJECTID	8081
Shape_Length	0
HOLE_ID	14024_FD85
EASTING	831878.4
NORTHING	839200.3
CATEGORY	1. Class I
TOP	-14.58
BOTTOM	-17.58
LENGTH_3D	3

Figure 9: Total core recovery attached to 3D Borehole Sticks (AECOM, 2024)

Currently, thirty-nine 3DGM blocks have been assembled for the proposed new towns in Fanling, Sheung Shui and Yuen Long using available GI data. All pilot 3DGM blocks have been uploaded to the 3DGInfo and are available for practitioners to use. To support the NMDAs, the GEO has accorded priority to expand the 3DGM blocks to cover these future development areas, such as the High-end Professional Services and Logistics Hub (i.e. Tin Shiu Wai, Hung Shui Kui, Ha Tsuen, Tsim Bei Tsui, Lau Fau Shan, Pak Nai and Yuen Long), Innovation and Technology Zone (i.e. San Tin, Lok Ma Chua and Ngua Tam Mei) and the Boundary Commerce and Industry Zone (i.e. Kwu Tung North, Man Kam To, Fanling, Sheung Shui and other northern districts).

3 ENGINEERING APPLICATIONS OF 3DGM

The pilot 3DGM enables instant assessment of ground conditions within a project boundary, significantly accelerating the creation of preliminary geotechnical models for better-informed decisions by planners and practitioners. This is particularly useful in preliminary planning, budgeting and schematic design of substructure works in projects. For example, practitioners can determine the spatial distribution of competent strata and the approximate founding levels of deep foundations. This facilitates a more efficient assessment of foundation options, as well as improving the estimations on the cost and time for the substructure works. The benefits and engineering applications of 3DGM are elaborated in the following sections.

3.1 Utilisation of valuable ground investigation records

The establishment of a territory-wide 3DGM is one of the best options to utilise and visually present comprehensive GI and laboratory testing inventory currently stored in the Digital Geotechnical Information Unit (DGIU). The GEO has collected over 370,000 GI records and associated laboratory test reports from various public and private projects since the 1980s. Despite the availability of some digital data in AGS file format, the majority of GI records in the DGIU are disseminated as scanned documents. This format is inconvenient for users who want to quickly appreciate the subsurface geology and ground conditions. Currently, practitioners have to download and review individual scanned reports from the DGIU, and extract data for subsequent use. The data are often manually entered into spreadsheets for processing in computer-aided design (e.g. CAD and BIM) and other engineering software. This manual extraction process can be error-prone and require laborious cross-checking that can take days. Furthermore, many practitioners usually lack a quick and efficient tool to visualise ground conditions before undertaking this time-consuming data extraction and CAD/BIM visualisation process. In essence, the 3DGM under 3DGInfo would provide practitioners a quick reference to readily visualise and understand subsurface conditions in a 3D perspective.

3.2 Efficient planning for site investigation

The 3DGM serves as an efficient tool for practitioners to systematically study regional geological conditions, identify potential constraints, and strategically plan site-specific GI works to mitigate uncertainties in ground conditions. Traditionally, during desk studies, GI planners should assess the relevance and spatial distribution of existing GI records and construct preliminary ground models or geological profiles for initial geotechnical assessments. In contrast, the 3DGM already integrates all available GI records and provides a reference model, significantly reducing the time and resources spent on repeating these processes across projects in the same region (Figure 10). Instead of building preliminary models from scratch, practitioners can explore the 3DGM to understand the subsurface conditions and extract relevant data for further analysis. Additionally, by overlaying geological maps within the 3DGInfo, practitioners can swiftly pinpoint areas with complex geological features, and plan targeted GI works as needed. The 3DGM further optimises GI planning by enabling simultaneous evaluation of stratigraphy and existing GI data locations, fostering data-driven decision-making during preliminary studies and site-specific GI design.

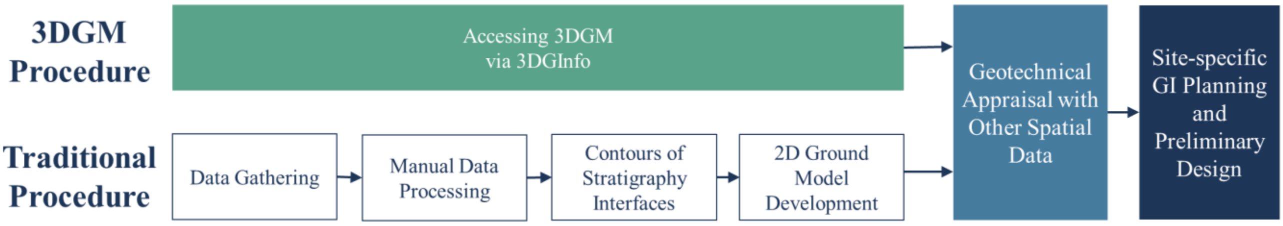


Figure 10: Prevailing engineering practice subsumed in 3DGM generation methodology

3.3 Interaction with different spatial data facilitating informed decision-making

The 3DGInfo integrates diverse datasets, enabling practitioners to visualise ground conditions alongside other spatial information and leverage synergies for project planning and risk assessment. For example, users can overlay geological maps, aerial photographs, tunnel protection zones, sensitive receivers (e.g., buildings, slopes), and topography with subsurface data within a unified 3DGInfo interface. This integrated approach extends beyond basic ground condition analysis, offering practical advantages for construction planning. Instant access to critical parameters, such as fill thickness, superficial deposit distribution, and groundwater conditions, streamlines the rapid evaluation of excavation and lateral support systems. For projects near sensitive structures (e.g., residential buildings, historical masonry walls, or underground tunnels), the 3DGInfo and 3DGM empower practitioners to assess potential impacts like ground movements, subsidence, and piling-induced vibrations/noise. These insights facilitate informed decisions on pile types and construction methodologies (Figure 11). Additionally, the system identifies risks such as structural loading on adjacent slopes or infrastructure, ensuring proactive mitigation strategies.

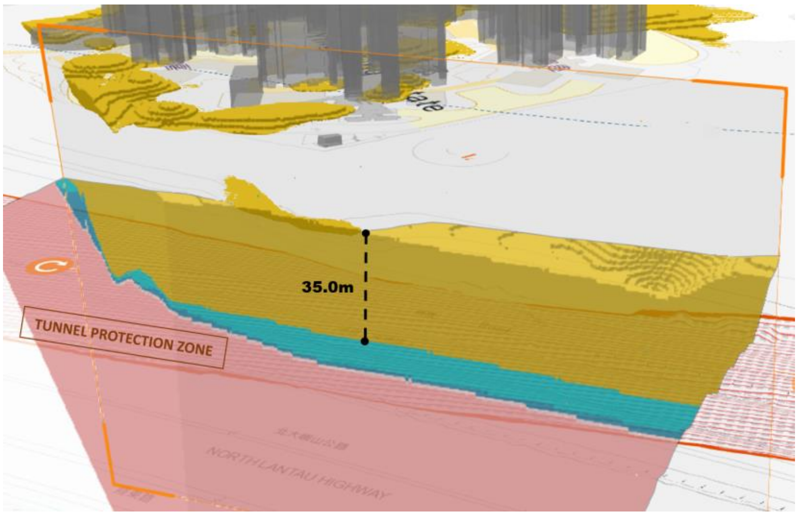
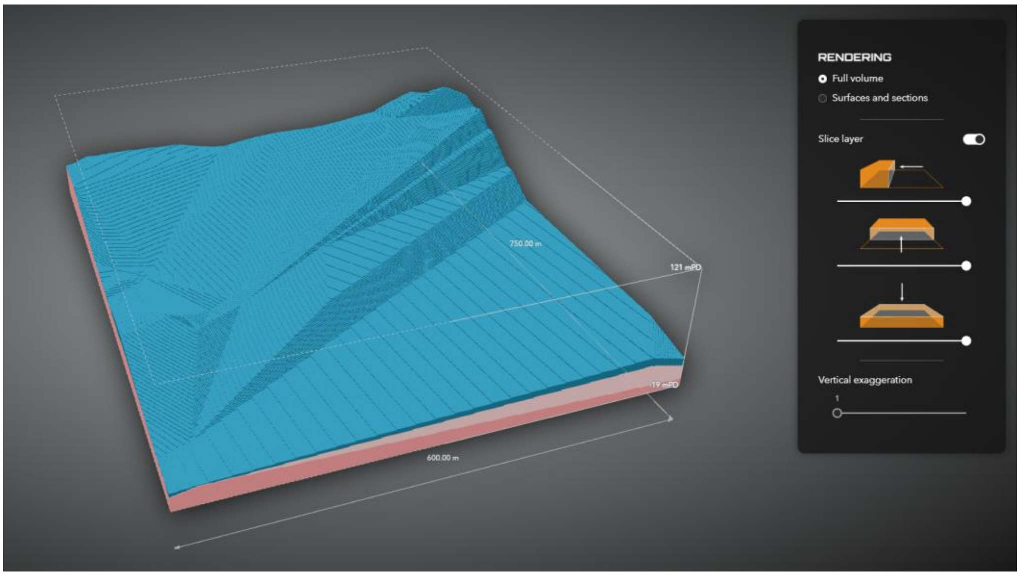


Figure 11: 3DGM overlaying with tunnel protection zone in 3DGInfo

3.4 Available geo-processing tools for 3DGM

In addition to visualisation in 3DGInfo, the interpreted stratigraphy (e.g. contours) and voxel data can be downloaded from the 3DGInfo in formats that could be used in other engineering software for contouring and GIS/BIM applications. This allows practitioners to integrate the data into their design workflows and GIS/BIM platforms. Several geo-processing tools are also available in the 3DGInfo to facilitate the use of the 3DGM, such as slicing tools for visualising the ground conditions in cross-sections. Figures 12 and 13 illustrate the available geo-processing tools for utilising the 3DGM within the 3DGInfo.

Figure 12: Geo-processing tools showing spatial distribution of ground materials at -35.0mPD



RENDERING

● Full volume

○ Surfaces and sections

Slice layer

Vertical exaggeration

1

Figure 13: Geo-processing tools displaying selected stratigraphy

4 CHALLENGES AND LIMITATIONS

Despite the successful implementation of the pilot 3DGM and its benefits for engineering applications, the current 3DGM generation methodology inevitably has limitations and definitely room for further enhancements. For example, the current workflow still relies heavily on manual processing when handling complex geological conditions, such as marble area, rock contacts, etc. The reliability of each 3DGM block is currently represented qualitatively by the superposition of 3D borehole sticks, but the reliability arising from different interpolation methods and geological variations cannot be properly quantified statistically.

4.1 Challenges in modelling complex geological conditions

In an attempt to model complex geology, the GEO created a pilot 3DGM in a marble site in Yuen Long (Figure 14). The modelling method of this pilot 3DGM is based on the karst geomorphology model (GEO, 1994). The presentation of the subsurface conditions with karst features suitable for founding deep foundations is fundamentally different from the conventional approach of representing other rock formations.

The karst geomorphology model employs a marble class system to categorise complex geological conditions in marble formations into a structured and abstracted framework. A key challenge in constructing deep foundations in marble formations is their highly variable nature and the presence of karstic features, such as overhangs, underground channels, cavities, and irregular rock surfaces. To streamline foundation design in such subsurface conditions, marble rock masses are classified into six distinct classes based on the percentage of the Marble Quality Designation (MQD) achieved in boreholes within predefined elevation levels. The MQD is computed from the core samples in boreholes and is a useful index to indicate the presence of dissolution cavities. Amalgamating zones of similar MQD will give the physical and mechanical implications of karstic features in the marble formation that can have a profound influence on the foundation stability.

In this system, Marble Classes I and II represent very good to good quality marble masses with MQD greater than 50%, and with no or minimal karstic features, making them ideal for foundation purposes. Class III defines fair to marginal quality marble mass influenced by karstic features, requiring detailed assessment to evaluate their impact on foundation stability. Conversely, Classes IV and V classify poor to very poor quality marble masses, heavily compromised by karstic features with MQD less than 25% and are typically unsuitable for foundations. Class VI, the final class, refers to non-marble rock types (e.g., interbedded layers) within the marble formation. This systematic approach enables practitioners to efficiently evaluate risks and tailor foundation solutions to site-specific conditions.

In the process of building the karst geomorphology model, the MQD of each borehole is calculated for the entire rock cores to derive the corresponding marble classes at every 5 m interval in the vertical elevation. The marble masses are then broadly grouped into competent marble classes (i.e. Classes I and II) and non-competent (i.e. Classes III to V) marble classes. Due to its inherent complexity, sound professional judgement is needed to develop a formidable geotechnical framework. The pilot 3DGM block digitised the categorised marble zone, similar to stacking Legos at 5 m intervals. This enables a 3D visualisation of karstic features within the marble rock formation (Figure 14). With the pilot 3DGM in such complex ground conditions, practitioners can now quickly identify possible zones of non-competent marble, for example, buried underground channels, and carefully assess its effect on the foundation design of high-rise buildings. For example, significant cost and programme advantages can be achieved by relocating building blocks to avoid installing piles in non-competent marble zones, thereby minimising costly construction and potential risk in foundation works. The 3DGM built for sites underlain by marble may be used for preliminary cost estimates and construction programmes.

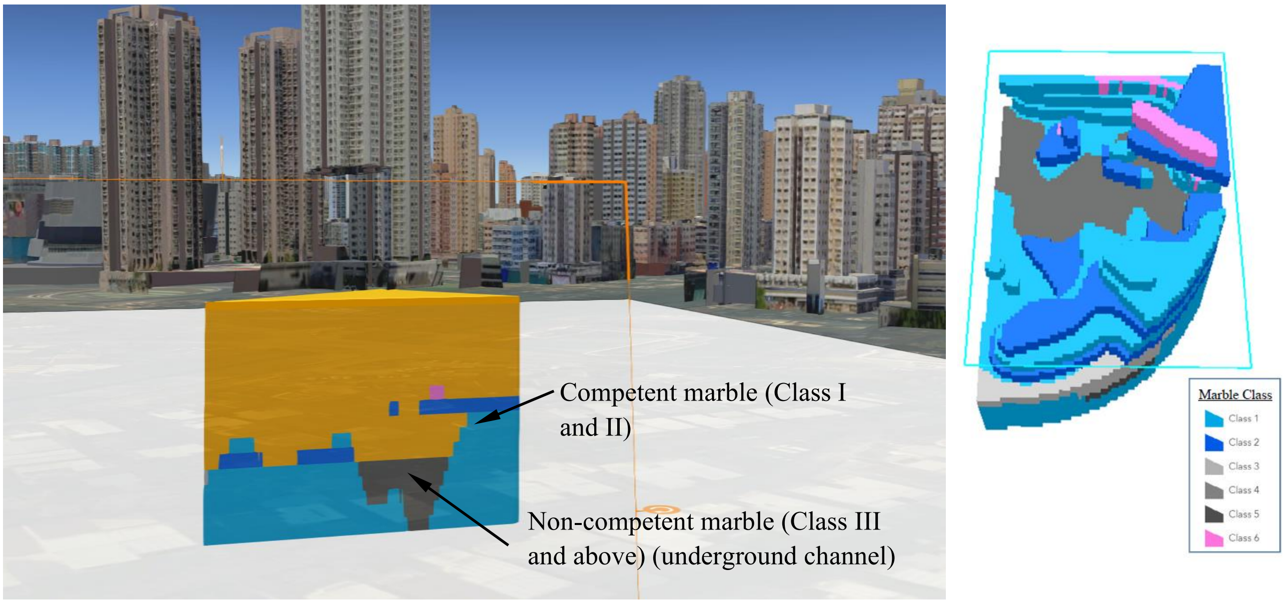


Figure 14: Pilot 3DGM block showing the karst geomorphology in a Yuen Long site

The current 3DGM generation methodology for marble sites relies heavily on manual scrutiny and professional judgement. For instance, decisions about the spatial distribution of marble classes across varying elevations often require expert interpretation. While the workflow outlined in Section 2 permits modifications to 3DGM by incorporating inferred rock contacts and adjusting sub-vertical boundaries, manual intervention is still required to delineate zones of abrupt geological change. More complex geological conditions, such as severe karstic features in fault zones between contacts of marble and intrusive rocks, are expected to require advanced modelling processes (Chan & Pun, 1994) to produce representative models for engineering assessments.

4.2 Ensuring reliability in the 3DGM

Communicating the reliability of the 3DGM to practitioners is crucial for their effective and safe applications. Since the generation of the 3DGM often involves interpretation and interpolation between GI data, it is essential to ensure transparency and provide flexibility in selecting the 3DGM generated using different modelling approaches. The GEO would implement several measures to assist practitioners in understanding the limitations of the data and modelling method.

The GEO is developing visual reliability indicators to guide practitioners in applying the 3DGM outputs appropriately. The reliability of stratigraphic interpretations depends on two key factors: the quantity and quality of GI data and the spatial variability of stratigraphy, such as the rate at which geological unit boundaries shift. To quantify this reliability, the GEO is leveraging machine learning technology to analyse stratigraphic variability in regions with similar geological settings. Additionally, the GEO is creating a reliability map based on the geospatial distribution of borehole data. Areas with dense borehole coverage typically exhibit higher reliability, while zones with sparse data reflect lower reliability due to greater reliance on interpolation. These visual indicators (Figure 15) will help practitioners assess confidence levels across different blocks of 3DGM, enabling more informed decisions in geotechnical planning.

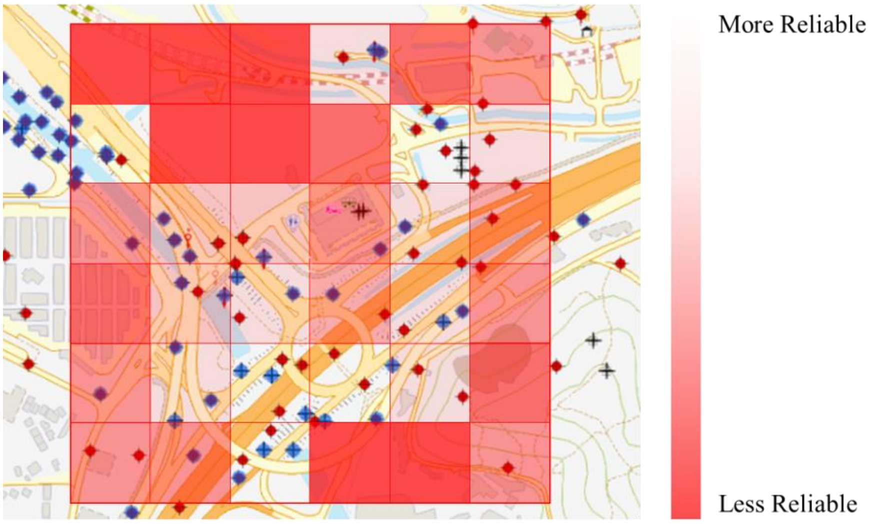


Figure 15: Conceptual graphical representation of reliability of stratigraphic interpretation based on borehole density

To ensure transparency, the GEO would provide clear and comprehensive information about each 3DGM, including descriptions of data sources, interpretation methods, model generation methods, resolution, etc. While attempting to include more advanced techniques to generate the 3DGM, the practitioners would be given the adopted interpolation methods for assessing its reliability. Cautionary remarks would also be attached to each 3DGM highlighting the limitations of the modelling technique and the need for expert verification on critical components, such as major unit boundaries or areas with highly variable material properties.

4.3 Other limitations

The accuracy of the 3DGM is inherently limited by the completeness and quality of available GI records in the target area. It is emphasised that the 3DGM should not be considered a substitute for thorough desk studies and site-specific ground investigation works. Instead, the 3DGM should be regarded as a supplementary reference tool for practitioners. Ultimately, practitioners remain responsible for developing project-specific geotechnical models coupled with site-specific GI data tailored to their unique project requirements. They should manage geotechnical risks in accordance with their professional judgement and the specific conditions of the site.

5 WAY FORWARD

The current 3DGM generation methodology still heavily relies on manual data processing, which severely hindered the timely development and update of 3DGM on a city scale. The GEO recognised the urgency of automating the existing 3DGM generation method in a more efficient manner.

5.1 Automation of 3DGM generation methodology

The GEO has been collaborating with local IT firms in developing a series of automated tools that will incorporate data validation and quality control processes for generating new 3DGM. Latest digital technologies would be adopted to streamline the complex design processes and replace repetitive manual procedures.

The automation process would begin by establishing a centralised digital GI database containing machine-readable data. While the DGIU holds a vast volume of GI records, most are scanned PDFs lacking digitised data in a consistent data specification, e.g. the AGS format. To address this issue, an automation tool would be developed to extract data from existing GI records (e.g., PDFs) and convert it into standardised digital GI data structure and format (e.g., MS Excel, CSV, AGS, JSON). This transformation would leverage machine learning techniques and advanced generative AI algorithms to ensure accuracy and consistency in extracting the data. The next phase involves creating a customisable 3DGM generator that allows users to select from various interpolation methods or algorithms. This tool would enable the generation of project-specific 3DGM tailored to unique engineering design requirements, ensuring alignment with technical and risk management objectives.

By leveraging the digital GI data, practitioners can unlock the full potential of the 3DGM generator by customising the 3DGM for diverse applications and seamlessly integrating them with numerical tools and CAD/BIM software. It is contemplated that the establishment of digital geotechnical models would pave the way for more design automation, enhanced efficiency, optimised geotechnical designs and cost reductions in engineering projects.

5.2 AI-enabled 3DGM generation methodology

In urban areas, existing GI data is often densely distributed, allowing simple interpolation methods to generate sufficiently accurate 3DGM. However, this is less viable in new development areas where existing GI data is sparse. In such data-scarce environments, traditional interpolation methods may become ineffective or impractical, leaving practitioners to rely heavily on professional judgement, and even speculative interpolation and extrapolation, to infer critical geological interfaces (e.g., rockhead levels) during preliminary project assessments. This may introduce significant variability in the accuracy of geotechnical assessment, as outcomes depend on the experience of the practitioner.

The GEO has collaborated with local universities to investigate the application of AI algorithms for interpreting subsurface conditions. This is achieved by analysing stratigraphic patterns in geologically similar settings. A fine-tuned AI model is being developed to identify and learn these patterns from analogous sites. By combining the AI-derived and trained stratigraphic patterns with available borehole data, an enhanced 3DGM can be generated. Unlike the conventional linear triangulation method, the AI model provides a systematic, controlled prediction of geological interfaces between widely spaced boreholes. It is anticipated that this will significantly outperform simplistic approaches like straight-line interpolation or speculative guesswork. Lyu et *al*. (2025) used this methodology in a study predicting stratigraphy at a reclamation site in Tung Chung, highlighting the advantages of a machine-learned, data-driven approach. The resulting AI-generated ground model serves as a preliminary reference for practitioners interpreting stratigraphy in data-scarce conditions (Figure 16).

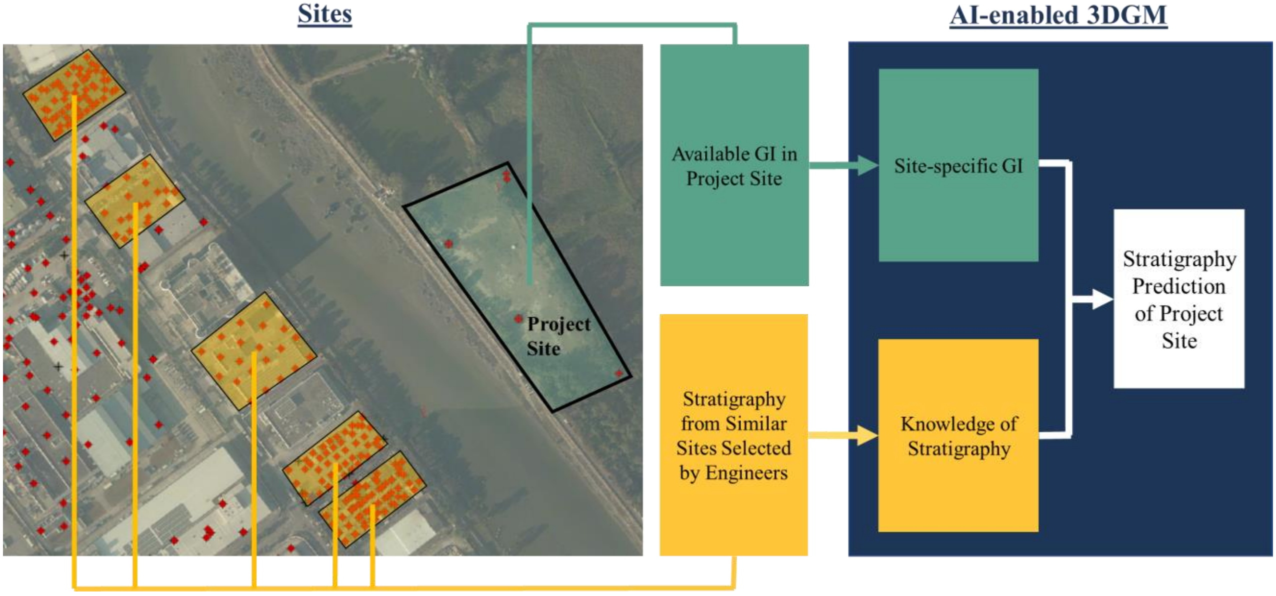


Figure 16: Conceptual diagram of AI-enabled 3DGM

5.3 *Wider engineering application of 3DGM*

The voxel-based 3DGM framework offers additional advantages, as each voxel cell can store multidimensional geotechnical variables (e.g., SPT-N values, shear strength, uniaxial compressive strength, unit weight, pore water pressure history). A centralised 3DGM inventory, acting as a laboratory and field test data repository, can unlock significant value. By aggregating geotechnical monitoring data from individual projects in the voxel cells, practitioners can design safer and more cost-effective engineering works, as historical data provide valuable information for future projects in adjacent areas or redevelopment of the same site.

Furthermore, integrating 3DGM with digital twins, incorporating data on foundations, excavation and lateral support systems, and underground utilities, can empower practitioners with enhanced insights into soil-structure interaction, enabling improved assessment of geotechnical risks and, consequently, the design of efficient engineering works.

6 CONCLUSIONS

Geotechnical engineering inherently involves postulating the subsurface ground conditions and applying engineering solutions to overcome construction challenges below ground. Whereas the current development of spatial data and 3D digital maps intuitively focused on ground level, such as the land topography and building blocks, the GEO recognised the need to drive the development of subsurface spatial data that would benefit the practitioners of Hong Kong at large. The GEO would continue to embrace the opportunity of rapid technological advancement and apply the latest machine learning and AI technology to promote smart and digital geotechnology.

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REFERENCES

AECOM 2024. *Review Report for the 3D Geotechnical Model Developed by GEO*, an unpublished report on Regional Geological Study of Northern New Territories (North) – Feasibility Study.

BD 2017. *Code of Practice for Foundation*. Buildings Department, Hong Kong Government, Hong Kong, 104 p.

Chan, Y.C. 1994. *Classification and Zoning of Marble Sites. GEO Report No. 29*. Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong Government, Hong Kong, 37 p.

Chan, Y.C. & Pun, W.K. 2004. *Karst Morphology for Foundation Design. GEO Report No. 32 (Second Edition)*. Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong Government, Hong Kong, 90 p.

Cheung, R.W.M. 2021. Landslide risk management in Hong Kong. *Landslides*, 18 (10), 3457-3473.

Cheung, S.P.Y. 2006. The application of information technology in managing landslide risk. *Symposium of the Science in Public Services*, Hong Kong, 12 p.

GEO 2006. GEO Publication No. 1/2006. *Foundation Design and Construction*. Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong Government, Hong Kong, 376 p.

Lyu, B., Wang, Y., Miao, C., Yao, J., Shum, L.K.W., Wong, A.L., and Ho, R.C.M. 2025. "Fusion of limited site-specific borehole Logs and geophysical data from a different site for three-dimensional subsurface geological modelling using Multi-Scale Generative Adversarial Network." *Journal of Geotechnical and Geoenvironmental Engineering,* accepted.

Shum, L.K.W., Cheung, S.P.Y., Tang, C.S.C., Ho, R.C.M., and Koo, R.C.H. 2024. Evolution of Three-Dimensional Geotechnical Information Infrastructure. *Proceeding of the HKIE Geotechnical Division 44th Annual Seminar*, 31 May 2024, Geotechnical Division, The Hong Kong Institute of Engineers.