

Evolution of Three-Dimensional Geotechnical Information Infrastructure

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ABSTRACT

Innovation has always been the priority of the Geotechnical Engineering Office (GEO) to unlock new possibilities and drive advancement in the engineering practice. In 2009, the GEO commenced the operation of the Geotechnical Information Infrastructure (GInfo), which is a digital infrastructure framework for developing and launching geotechnical applications for practitioners and the public. It has since become the authoritative source of geotechnical information in Hong Kong. In recent years, there are remarkable advancements in 3D visualisation and data capturing technologies that revolutionise and transform the way that 3D objects and spatial data are created, analysed and communicated in an immersive and realistic visual representation. Riding on these advancements, the GInfo was migrated to 3DGInfo that creates a new horizon for smarter applications. More 3D objects and spatial data are generated using novel technologies, such as pulsed-laser scanning, photogrammetry and BIM modelling. GEO is also capturing photorealistic 3D mesh models, such as man-made features, landslides, tunnels, etc., to enhance the user experience. In parallel, a 3D geotechnical model (3DGM) is being assembled with existing GI records kept by GEO. The 3DGM will assist planners and engineers with a quick reference of the geology and ground conditions of their development site. The 3DGInfo also acts as the backbone of the GEO digital twin platform that connects the physical and digital world, where predictive analysis can provide simulated scenarios with greater sophistication in visualisation and immersive environment. This paper discusses the smart technologies and innovative solutions provided in the 3DGInfo, that aim to enhance the GEO services and benefit the practitioners.

1 INTRODUCTION

GEO is always taking a steering role in development of innovation and technology (I&T) for slope safety in Hong Kong. Some successful engineering applications are presented in Cheung (2006) and Cheung (2021). Recently, GEO has completed the project of enhancing the Geotechnical Information Infrastructure (GInfo). One of the main enhancements is the strengthening the three-dimensional (3D) visualisation capability of GInfo, such that the 3D spatial data and objects are organised and presented in a truly 3D representation with greater sophistication on their details and spatial correlations. The three-dimension GInfo (3DGInfo) comes into operation in September 2023.

As part of the enhancement works, the 3DGInfo is migrated to a cloud platform which improves the resilient and reliability of this infrastructure framework. This is important for the critical systems that support GEO emergency services, such as Slope Information System, Landslide Information System, Mobile GInfo Application, GEO Rain Gauge System and Landslip Warning System. In addition, computing resources in the cloud platform are highly scalable and can be upscaled easily to meet any sudden surge in the demand of computing resources where situations warrant. The interface mapping capability is also improved by using the cloud rendering technology, where parsing and rendering highly sophisticated and detailed 3D models are done in the remote servers. The levels of detail and data size of 3D objects and models have increased significantly for better visualisation and representation, such as the LandsD 3D spatial data model, BIM as-



built model, ground feature and digital terrain model captured by Light Detection and Ranging (LiDAR) scanning and photogrammetry technology, etc. Cloud computing provides the efficient rendering solution which is a prerequisite for enhancing the user experience when browsing and analysing the 3D models and spatial data in the 3DGINfo.

Besides improving the infrastructure and computing capability of the 3DGINfo, it is also essential to create 3D object and spatial data that can simulate the real-world environment and provide contextual information, spatial relationships and real-time monitoring capabilities. Traditionally, 3D spatial data in GIS are captured and presented in a two-dimensional coordinated mapping space and the third dimensional values is then represented by cartographic symbols. In recent years, advancements in remote sensing technology, such as LiDAR scanning and photogrammetry, and retrieval algorithms have significantly improved the data quality with real world textures and photorealistic impression. GEO has invested on these technologies and developed affordable solutions that can capture and build highly sophisticated 3D objects, e.g. photorealistic mesh models of man-made feature, landslide, etc. The display of these models in 3DGINfo requires substantial rendering power for effective uses. In addition to capturing and managing 3D objects and spatial data above the ground surface, GEO is also developing a 3D Geotechnical Model (3DGM) to represent the subsurface conditions of Hong Kong, with emphasis on their implications to the engineering works (e.g. founding levels of pile). The 3DGM in some pilot study areas has already been incorporated in the 3DGINfo.

It has been one of the GEO strategic developments to establish a digital twin platform for enhancing the GEO services and improving decision process with better understanding of the unfolding severe weather event. The 3DGINfo also serves as the backbone of the digital twin platform which provides the connection between physical and digital world. When GEO data are managed and maintained centrally in the 3DGINfo and on a cloud platform, it provides the opportunity to make use of cloud computing and artificial intelligence technology to carry out big data analytic to uncover insights from structured and unstructured data of GEO to advance the engineering practice, improve the services and enhance the operation efficiency.

2 3D SPATIAL DATA IN THE CENTRAL REPOSITORY OF 3DGINFO

It is well acknowledged that data is the main ingredient of any successful digital solution. GEO is capturing and creating lots of 3D spatial data to support the 3DGINfo. Existing 2D spatial data (e.g. slope feature boundary, land lot, country park boundary, railway protection zone) can be incorporated into the 3DGINfo by projecting their planar boundary into the digital elevation model (DEM) or converting them into 3D models based on available as-constructed drawings (e.g. existing tunnels and caverns). However, such conversion may not satisfy and meet the needs of the user, when it comes to the positional accuracy and levels of detail of the converted 3D model. The methodologies of capturing 3D data and creating models are continuously modernised and enhanced. Nowadays, 3D models are routinely created by high-resolution satellite imaging, UAV-based laser scanning and photogrammetry and extraction from as-constructed BIM of the engineering works. The GEO also works with relevant parties in expanding the contents of the 3D spatial data in the central repository of the 3DGINfo.

2.1 3D models of the cityscape by the Lands Department

The success of the 3DGINfo rides on the comprehensive 3D spatial data developed by the Lands Department (LandsD), which is a key milestone to transform Hong Kong to a smart city. The land features include buildings and infrastructures for the entire Hong Kong and the levels of detail can provide highly photorealistic city models for visualisation. The base map of the 3DGINfo is built on the 3D spatial data that are completed timely by LandsD in 2023 (Figure 1). By superimposing the available 3D spatial data onto the digital elevation model (DEM) constructed with the 2020 airborne LiDAR survey, the 3DGINfo is capable to replicate the entire Hong Kong city in a virtual 3D environment. The visualisation map will help facilitate the execution of works projects, slope engineering studies, town planning, spatial analysis, simulation, application for smart mobility and other feasibility studies.

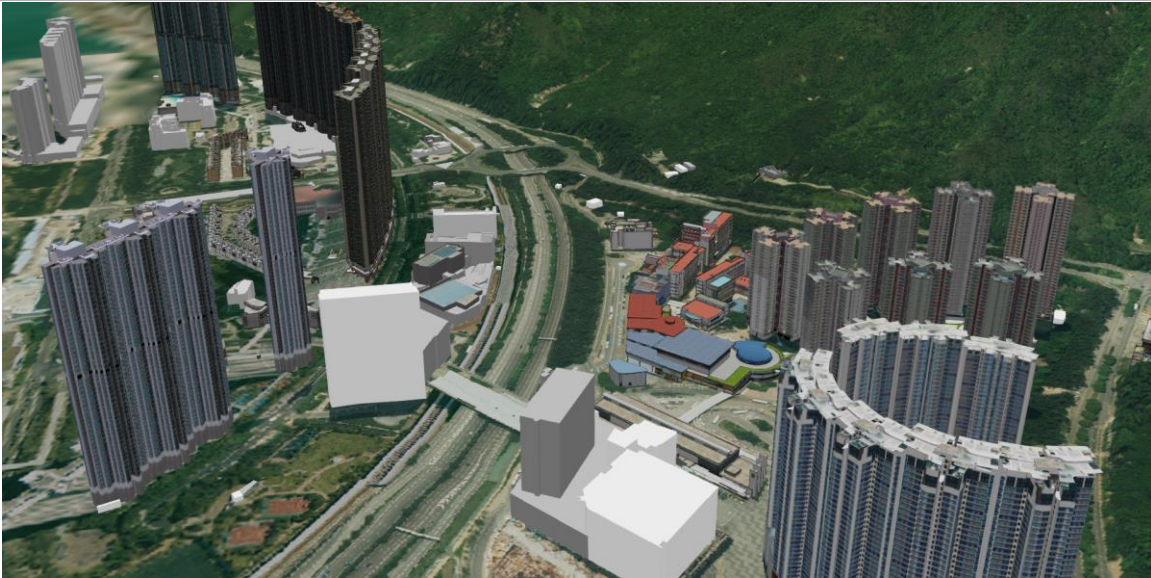


Figure 1: The base map of 3DInfo assembled using the spatial 3D objects produced by the Lands Department

2.2 BIM models of engineering work

It has been the Government strategy to adopt Building Information Modelling (BIM) to enhance the productivity of the construction industry in Hong Kong. Over the years, various policies and measures have been rolled out to support the use of BIM in public works and private projects. Since 2018, GEO has incorporated the BIM technology in the design and construction of major slope works (e.g. soil nailing, flexible and rigid barriers) under the Landslip Prevention and Mitigation Programme (LPMitP). Apart from on-going projects which BIM has already been adopted for design and construction, GEO has initiated the exercise of gradually digitising and creating BIM models of natural terrain hazard mitigation measures (NTHMM) that were completed years ago. Under this exercise, the GEO has utilised the as-constructed records and additional LiDAR survey data to create BIM models for NTHMM (e.g. debris-resisting barriers). In digitising the as-constructed NTHMM, contextual information such as project details, material properties, key data (e.g. energy rating, brake element model) of the defensive measures are also embedded in the BIM model. Figure 2 shows the high-level details of the flexible barrier that could facilitate future maintenance.

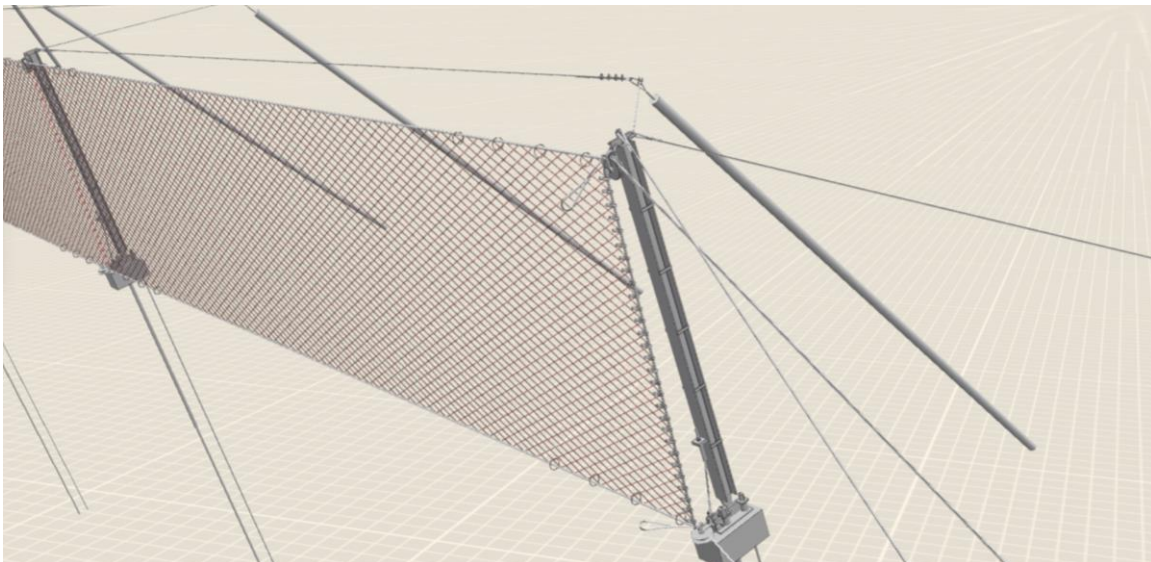


Figure 2: Flexible barrier with high levels of detail converted and embedded in 3DInfo

In recent years, there has been significant progress in the integration of BIM models into GIS environment and it becomes easier to turn design and construction data embedded in the BIM model into GIS assets. Available as-constructed BIM models of the geotechnical works carried out under the LPMitP are also uploaded to the 3DInfo (Figure 3). There are ample potentials to make use of these BIM models to facilitate the maintenance agents to maintain the NTHMM or to turn them to digital twins with real-time IoT sensors.



Figure 3: BIM models of as-constructed NTHMM in 3DInfo

2.3 Point cloud and photorealistic mesh model using LiDAR survey and photogrammetry

The Survey Division of CEDD has been supporting GEO with taking LiDAR survey on unmanned aerial vehicle (UAV) of area of interest from time to time. The deliverables include high quality photorealistic 3D mesh models, point clouds and loads of aerial photographs. These are important assets that provide the snapshot of the ground features at the time of inspection and they are systematically uploaded to the 3DInfo for proper management and temporal change analysis at later stage. The Survey Division always accords high priority of capturing landslide features whenever requested by GEO. It was timely that the 3DInfo was available in early September 2023 ahead of the extreme rainstorm event that followed. Photorealistic 3D mesh models of many significant landslide were captured and uploaded to 3DInfo. These 3D models provided a quick overview of the landslide source uphill, which was otherwise difficult to be inspected from downslope. The landslide source volume could also be estimated by comparing the 3D model of the landslide scar with the digital terrain model based on 2020 LiDAR survey. The information greatly facilitated GEO officers in assessing the residual risk, together with a better representation of the spatial distance between remaining debris and threatened facilities. Some examples of landslide photogrammetry models created during the extreme rainstorm events in September and October 2023 using UAV survey are illustrated in Figure 4.

The drone flight paths are also stored and presented in the 3DInfo. This facilitates users to retrieve any aerial photograph taken during the flight (Figure 5). The flight path can also be used as reference for the repeated drone inspection to create the latest ground feature model for temporal change analysis. Figure 6 shows the latest conditions of the landslide at Yiu Hing Road in February 2024, which is useful to assess the residual risk after the implementation of the emergency works.



(a) Kam Shue Road



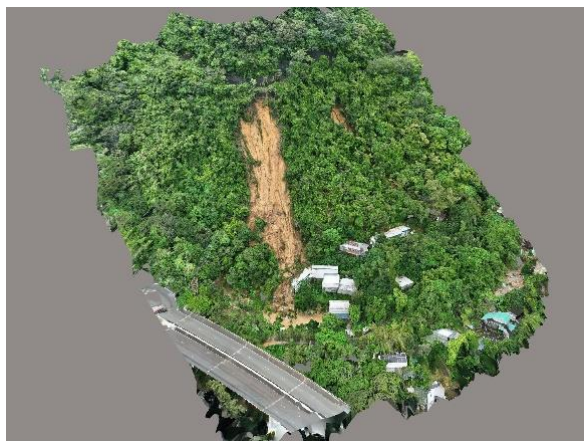
(b) Shek O Road



(c) Ping Chi Street



(d) Red Hill Peninsula



(e) Pak Tin Village



(f) Yiu Hing Road

Figure 4: Photogrammetry models of landslide event in September and October 2023

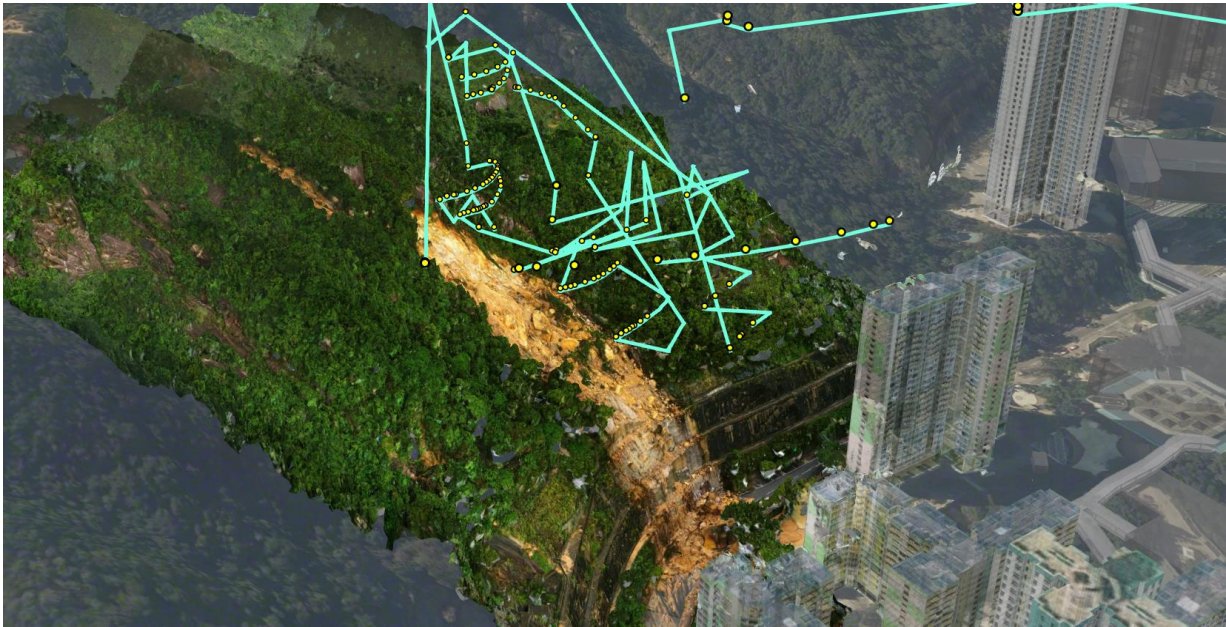


Figure 5: Site specific LiDAR data and drone flight path of Yiu Hing Road landslide site in 2023



Figure 6: Condition of the landslide site at Yiu Hing Road in February 2024

2.4 Highly detailed photorealistic mesh model by handheld remote sensing device (Pano360)

GEO has collaborated with the Mechatronics and Robotic System (MaRS) Laboratory of the University of Hong Kong and a local IT firm to develop an affordable handheld remote sensing device (Pano360) for capturing and creating highly detailed photorealistic 3D models. The application of the Pano360 is widespread, which can be used in capturing the details of failure scar before surface protection are applied; or taking snapshots of the ground feature during site inspection and preparing the slope inventory during routine or engineer maintenance inspection of features. Figure 7 shows the site inspecting personnel carrying the Pano360 and traversing the area of interest in normal walking manner. Figure 8 shows the levels of detail of the 3D spatial model of slope feature No. 11SE-C/C717 at Tai Tam Reservoir Road that were created with Pano360. It could upend the conventional way of compiling slope inventory record with a few discrete aerial photographs. It is planned to promote the usage of Pano360 amongst geotechnical consultants.

The quality of the slope inventory in the 3DGIInfo will gradually be enhanced when more 3D spatial models of man-made slope feature are created.



Figure 7: Inspecting personnel holding Pano360 for capturing pictures to form the photorealistic mesh model of the landslide site at Yiu Hing Road



Figure 8: Photorealistic 3D mesh model of 11SE-C/C717 at Tai Tam Reservoir Road that is superimposed to the terrain based on aerial photographs

2.5 3D Geotechnical Model

The Geotechnical Information Unit (GIU) currently holds more than 370,000 GI records collected over the years. The GI records are mainly managed and disseminated in the GIInfo as scanned records, which are ineffective for the users to quickly understand the geology and ground conditions at depths. In recent years, voxel-based modelling has gained popularity in representing the space complex and discrete volumetric objects. Voxels are small cubed shaped units of volume that can be arranged in a 3D space to form objects of any size and shape. They are particularly suitable to represent irregular and discrete objects, such as terrain and geology. With the advancement in this modelling technique, it is feasible to build the 3DGM of Hong

Kong that could facilitate planners, practitioners and the public to appreciate the subsurface geology and ground conditions pertinent to different engineering applications.

Unlike a geological map, the 3DGM would emphasize on their relevance in engineering applications based on the interpretation of the engineering properties of the material encountered at depths. For example, delineation of stratigraphic interfaces is based on the tentative levels of different type of foundation (e.g. driven steel H piles usually are driven to refusal at soil stratum with SPT 'N' value greater than 200; deep piles founded on Cat. 1(d) and Cat. 1(c) rock profiles that have different presumed bearing capacity in accordance with current practice for foundation works). Certainly, there will be unavoidable limits arising from the completeness and adequacy of GI records within a study area, which can affect the accuracy of the delineated stratigraphic interfaces. Nevertheless, it should not defeat the purpose of 3DGM to provide quick and preliminary information to users of the ground conditions within the boundary of their project. On the other hand, the 3DGM is not a replacement to site-specific ground investigation works, which are important to provide sufficient site-specific details for the design of any geotechnical works and avoid unacceptable construction risks. The 3DGM could be further refined when additional and site-specific ground investigation are available at the subsequent stages of the project.

Completing the 3DGM for the entire Hong Kong will be a substantial task and it is intended to start the 3DGM with blocks of small area based on map sheet delineation (e.g. 1:5,000 map sheet no. 11SW-14B with a dimension of 750m × 600m). The first pilot study examined about 1,000 GI boreholes within and around the map sheet and Figure 9 illustrates the 3DGM under part of Wan Chai area. Besides visualising in 3DGMInfo, all the interpreted data that are used to create the voxel models (e.g. the textual data and TIN surface representing the interfaces) can be downloaded for further engineering analysis by users. Using map sheet delineation allows flexibility in selecting the priority areas for developing 3DGM. For example, the regional geotechnical study for the Northern Metropolis Region will also produce a 3DGM for the study areas and be incorporated into 3DGMInfo when available.

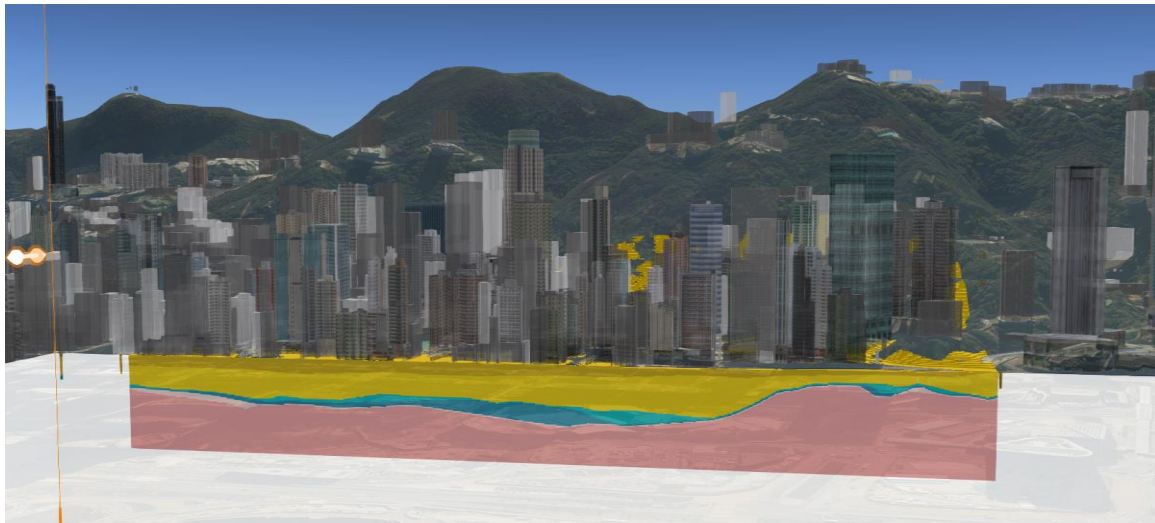


Figure 9: 3DGM in Wan Chai (Map Sheet No. 11SW-14B)

A different approach has to be adopted when it comes to representing the ground conditions of marble rock formation for foundation design. It is very common to find the marble rock formation in Hong Kong to be severely affected by dissolution process, resulting in many karstic features (e.g. presence of overhang, underground channels and cavities, highly undulating rock surfaces, etc.) that pose significant difficulty for deep foundation works. It is the practice to develop site-specific karst geomorphological model that is based on stratifying the site into multiple strata of fixed thickness (e.g. 5 m) and then delineating competent and non-competent marble within each stratum. By overlying the strata together, the 3D karstic features within the marble rock formation can be visualised. The voxel-based modelling is excellent for representing the highly

irregular karstic features in a 3D space. A separate workflow has been developed where different marble zones are assembled by cubes, such as stacking Legos. Figure 10 shows the 3DGM for a Yuen Long site with zones of different marble class. The 3DGM allows users to quickly identify competent marble mass zone (i.e. Classes I and II) and provide preliminary information for placing high-rise building away from weak marble mass zone (i.e. Classes III, IV and V).

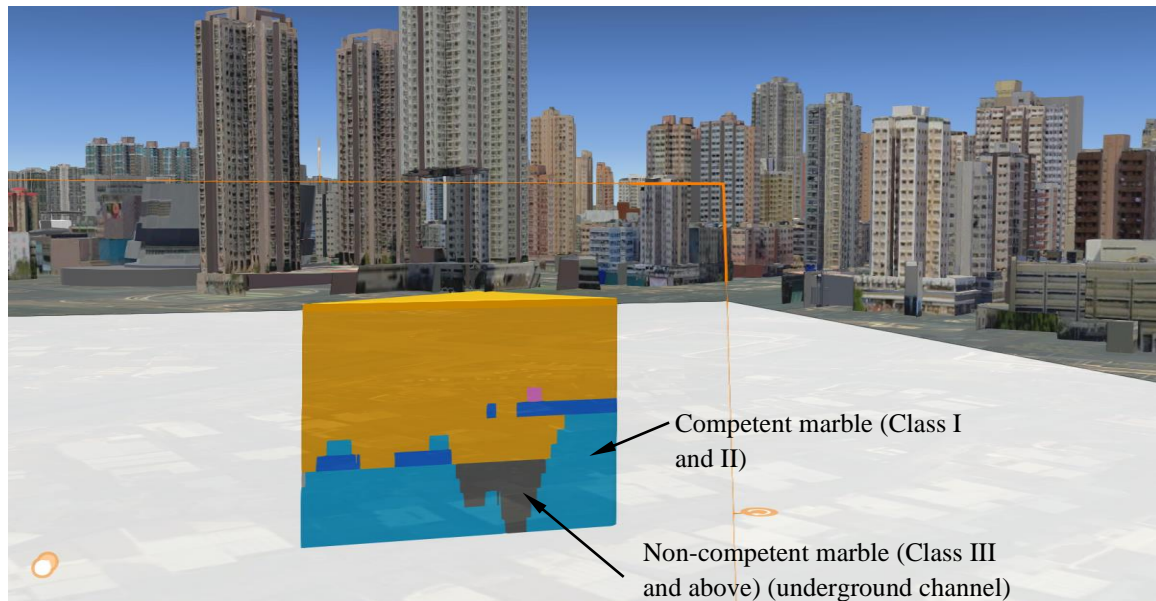


Figure 10: 3DGM showing the karst geomorphology in a Yuen Long site

3 NEW IMPETUS OF THE 3DGInfo

3.1 Development of GEO Digital Twin Platform

Digital twin is a dynamic and responsive system connecting the physical and digital world, where predictive analysis provides simulated scenarios with greater sophistication in virtual reality visualisation and immersive environments. A well-designed digital twin can transform many organisations in their ways of managing the complex and dynamic real-world environment. In recent years, the digitalisation of the built environment has been greatly enabled by the advancement in digital technologies, notably in the fields of remote sensing, real-time monitoring sensors and Internet of Things (IoT) and virtual reality simulation engine. Establishing a digital twin platform under the 3DGInfo is one of the GEO strategic developments to enhance the services and improve the decision process with better understanding of unfolding scenarios.

There is no lack of such systems in GEO that integrate real-time data in the physical environment and provide predictive scenarios for decision making. An early example is the GEO Landslip Warning System that was first deployed in 1980s, with rainfall data collected in every five minutes at rain gauges installed in different parts of Hong Kong. The rainfall data are fed into predictive models for analysing the increase of landslide risk during severe rainstorm event. The results of the prediction often provide the basis of deciding the necessity of issuing Landslip Warning to the public.

Another example is the Po Shan Drainage Tunnels that are constructed at Po Shan, Mid-levels in 2009. The stability of the hillside was affected by high groundwater level and the drainage tunnels, comprising a network of 172 sub-vertical drains, were constructed to regulate the groundwater level in the soil mass and reduce the landslide risk in the region. The groundwater level is continuously monitored by the pressure gauges installed on the sub-vertical drains and the piezometers in the slope above. A pressure relief valve is mounted at the end of the sub-vertical drains and it will automatically open and close to keep the groundwater level within pre-defined ranges. The monitored data are transmitted to a central interface in every

15-minute with modern pressure sensor equipped with IoT devices. These are used for interpreting the location of the groundwater level and comparing the rainfall reading from the nearby rain gauge stations.

Barrier are commonly constructed to mitigate the landslide hazard arising from natural hillside. However, they are very often erected at the foot slopes of hillside and stream courses where accumulation of landslide debris behind the barriers may easily go unnoticed. GEO has developed the Smart Barrier System (SBS) with the installation of state-of-the-art IoT and detection sensors. When the barriers are hit by landslide debris, instant alert will be sent to responsible officer, who will then assess the need for inspections and follow-up actions to ensure public safety. The detection sensors include impact switches for detecting debris impacts, depth gauges for measuring thickness of debris accumulated behind the barriers, and cameras for confirming field condition and screening out false alarms. Currently, smart barriers are installed at strategic locations protecting important facilities and residential dwellings, including Braemar Hill, Sham Tseng, Queen Mary Hospital, Shatin Hospital and Tate’s Cairn Highway.

The enhancement of the 3DInfo provides the opportunity of centrally managing different GEO IT systems in the digital twin platform and bringing in better visualisation of the site setting environment with real-time monitoring data and predictive scenarios. This enables prompt review of the performance of facility and their surrounding environmental conditions. Digital twin has already been set up under the 3DInfo for the SBS (Figure 11) and the Po Shan Drainage Tunnels (Figure 12). This greatly enhance the effectiveness of information dissemination among the different action parties during severe rainstorm events and will be detrimental to making informed decision by respective officers.

3.2 Other Potential Development

The potential of digital twin technology in building management is enormous and diverse. GEO is currently implementing the projects of reprovisioning the Public Works Central Laboratory and building a new Archive Centre in the caverns at Anderson Road ex-quarry site, which will be completed in 2026. It is planned to create a digital twin for representing the entire buildings and the assets inside, including the laboratory equipment, structural elements, HVAC systems, lighting, and even occupancy patterns. The digital twin will integrate real-time data from IoT sensors and mirror the state of a building and equipment, simulates future scenarios, and provide actionable insights for efficient operation and management.

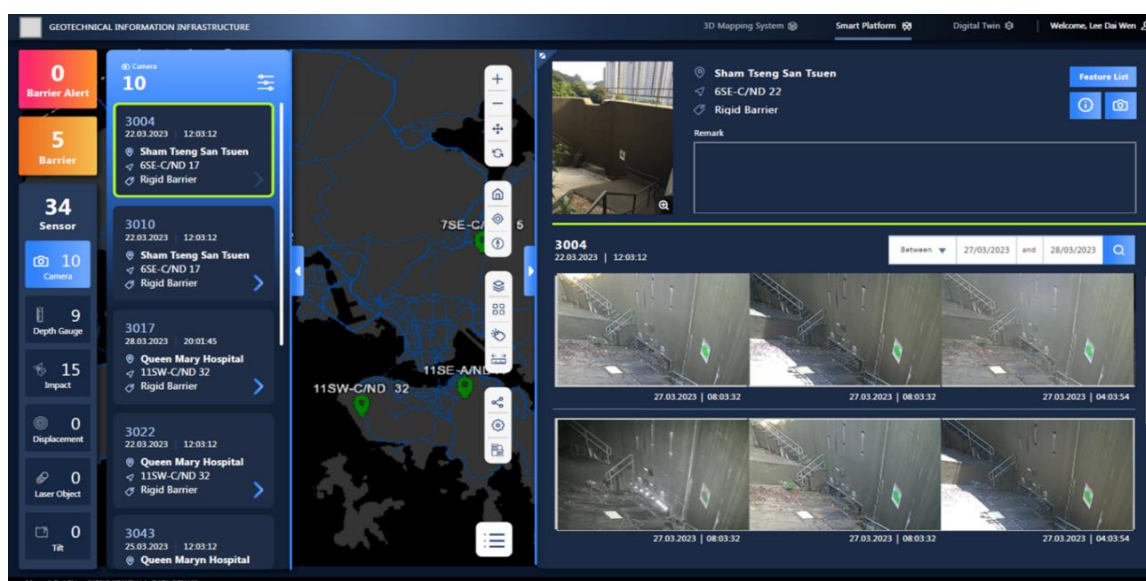


Figure 11: Digital twin of Smart Barrier System

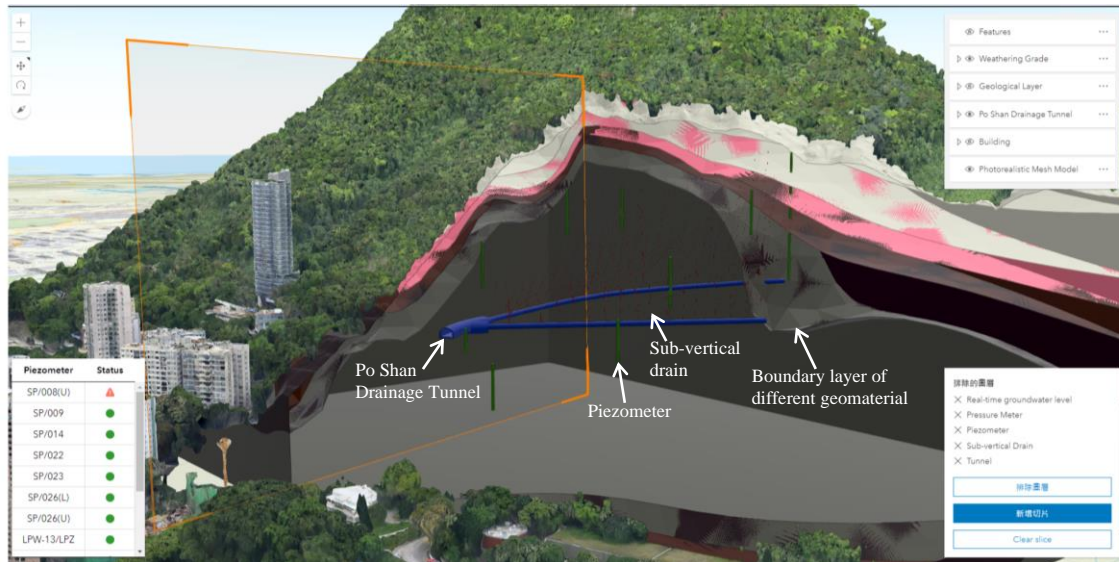


Figure 12: Digital twin of Po Shan Drainage Tunnel Monitoring and Operation System

4 WAY FORWARD

The development of the 3DGInfo provides the necessary infrastructure for managing and processing large amount of 3D spatial data that could replicate the real-world environment. As a centralised platform operating on cloud, the opportunities of further digitising the slope inventory and land features using the modern data collection techniques are ample. Spatial data is inherently 3D, such as the land topography, the built environment of the city, and even subsurface geology, and these can now be displayed not only intuitively and visually in the 3DGInfo, but also in a quantifiably and measurably representation. Data analytic based on all 3D attributes and even temporal change can now be carried out and further developed. GEO has been working on using machine learning techniques to improve the prediction in different areas of interest (e.g. rainfall and landslide correlation). As a logical step, the dataset in the cloud platform and the versatility of the cloud computing could set the scene for developing AI-based solutions in the 3DGInfo in future to facilitate more smart applications for slope safety management in the GEO.

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REFERENCES

- 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.