Smart Construction Monitoring Using Photogrammetry and LiDAR-derived 4D Digital Model: A Case Study from the Tung Chung New Town Development of Hong Kong

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ABSTRACT

The conventional practice of construction site monitoring in Hong Kong relies heavily on in-person site inspection, which is inherently subject to limitations in human resources, health, safety and time. Additionally, given that the advent and application of new digital technologies in the construction industry predominantly occurred after 2010 in Hong Kong, it is more challenging to review/ monitor the changes of a construction site with respect to its historical (pre-2010) status. To overcome these limitations, in this paper, we present the use of the 4D model monitoring method on a case study from the Tung Chung New Town (TCNT) and its extension development in Hong Kong. Nine 3D digital surface models covering a 57-year time period from 1963 to 2020 were built from the historical aerial photographs using the Structure from Motion technique and from the territory-wide airborne LiDAR data. These models were used for monitoring the process of land reclamation, site formation and the subsequent works during the TCNT development. In addition, a preliminary ground model was constructed from approximately 500 Nos. of drillholes to provide an engineering geological background for the study site. It is promising that our innovative 4D digital model and the associated sub-surface rockhead model can be integrated with the Building Information Modelling (BIM) system at a later stage to constituent a Smart Built Environment and to facilitate a smart construction site monitoring practice in near future.

Keywords: Smart Construction Monitoring, 4D Digital Model, Photogrammetry

1 Introduction

1.1 Background

The conventional industry practice in construction monitoring, particularly for site formation works, involves an in-person site inspection and the use of site photos or videos taken by unmanned aerial vehicles (UAV). These aerial photographs will be taken at different altitudes, different angles, different resolutions, and at different locations of the construction site at certain time intervals as stated in the contract. The details of the construction progress and site overview can be recorded and tracked from these monthly photographs. However, limitations were found with carrying out the monitoring in an oversimplified 2D format. Even with the adoption of some advanced technological methods in recent years for construction monitoring, including thermal surveys using thermal cameras mounted on UAV, handheld LiDAR surveys, and the use of online platforms (e.g., Aerial Cloud) for data acquisition and management, some are subject to significant limitations in time and cost, especially when it is necessary to monitor a relatively large construction site for a prolonged period of time. Besides, challenges were also found in monitoring changes in a construction site with its historical status due to limitations in technologies at that time. With the rapid development of different geospatial and geotechnical software together with more open geospatial data available in recent years, a more advanced technological

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approach can be used in tackling some of the constraints present in the latest construction monitoring practice. In this paper, we present the use of the 4D digital model monitoring method on a case study from the Tung Chung New Town (TCNT) and its extension development, by building and comparing multi-temporal 3D digital ground surface models from historical aerial photographs and the available airborne, territory-wide LiDAR data. Nine surface models were built for the years 1963, 1993, 1998, 2000, 2001, 2004, 2010, and 2020 (two models for 2020). The pre-2010 and one of the 2020 surface models were built from historical aerial photographs using the Structure from Motion (SfM) technique. The remaining two recent models were built from the available 2010 and 2020 airborne LiDAR data respectively.

1.2 Study Area

The study area is located in the northern part of Lantau Island, which includes the existing Tung Chung New Town Centre, Tung Chung North, and Tung Chung (East) New Town Extension, which is now undergoing reclamation and construction (Figure 1). The constructed 3D digital models would mainly focus on land reclamation and site formation of Tung Chung Town Centre, Tung Chung North, and Tung Chung (East) New Town Extension under the Tung Chung New Town Development Project.

1.3 Construction Process of the Tung Chung New Town Development

The study area is part of the general new town programme launched in 1973 with TCNT being the ninth new town developed in this programme. The existing TCNT is situated on the northern side of Lantau Island (ARUP, 2015). The engineering construction work for Tung Chung New Town Development Plan has been divided into four major phases since its commencement. Phase 1 of Tung Chung Development was part of the Airport Core Programme Project and was completed in January 1997. The engineering work in Phase 1 includes site formation, construction of different infrastructure including roads, drains, and sewage treatment facilities (Civil Engineering and Development Department, 2020). This phase of construction work involved reclamation work of a total of 67 hectares.

Phase 2 of Tung Chung Development was divided into Phase 2A and Phase 2B. Each of the phases was completed in May 2000 and February 2001, respectively. Phase 2A involved reclamation works and construction of the associated infrastructure. They were completed in January 1997 and May 2000 respectively (Civil Engineering and Development Department, 2020). The reclamation work involves 35 hectares of reclaimed land, located due north of Yat Tung Estate (Hong Kong Place, 2021). Phase 2B involved engineering works including site formation and infrastructure. This phase was completed in February 2001.

Phase 3A of Tung Chung Development mainly focused on reclamation work which was completed in April 2003. This involved 26 hectares of reclaimed land located due north of Ying Hei Road with the use of public fill (Civil Engineering and Development Department, 2020; Hong Kong Place, 2021).

The last phase of Tung Chung New Town Development, which is the Tung Chung New Town Extension project involves a total possible development area of about 240 hectares with about 124 hectares of reclaimed area at Tung Chung East and Tung Chung West (ARUP, 2015). Apart from reclamation work, this stage of construction work will also involve construction of associated infrastructure.

1.4 Geological Conditions

According to the studies on the geological conditions of Northshore Lantau carried out by the Geotechnical Engineering Office (GEO), Tung Chung (East) New Town Extension is located within the Northshore Lantau Designated Area, which is potentially underlain by complex geological conditions (GEO, 2021). Those complex geological features include anomalously deep and inclined rockhead with mainly weathered intrusive igneous rocks, carbonate-bearing rocks which would give rise to cavities and cavity-fill deposits, massive marble with a karstic upper surface displaying solution features, and superficial deposits which indicate the potential occurrence of other complex ground features (GEO, 2004, 2021). In view of the complex geological conditions, it is suggested that detailed geophysical (gravity) survey instead of the conventional ground investigation techniques (drilling and seismic reflection profiling) shall be used for identifying the location of the deeply weathered zones (Environment, Transport and Works Bureau, 2004). Besides, the complex geological conditions may also give rise to problems associated with construction involving deep foundations. Adequate resources and geotechnical input would be required in designing and constructing the foundations (GEO, 2021).

One of the signature obstacles in engineering work of TCNT associated with the complex ground conditions is the abandonment of proposed tower 5 due to the problematic geological conditions found in 1996 when drilling for Tung Chung Town Lot 3 (Figure 2) (Sewell & Kirk, 2002). Both cavity-filled facies and collapsed facies were found below 100m from ground, indicating the presence of cavities formed from dissolution of marble-bearing granite (Sewell & Kirk, 2002).

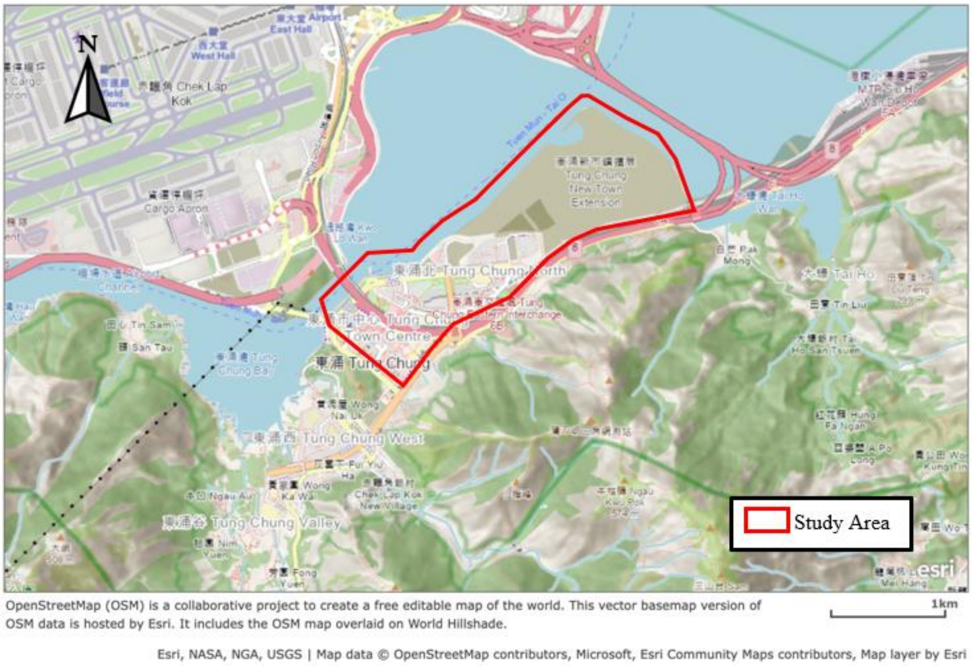

Figure 1: Location of the study area. Basemap is from Esri OpenStreetMap.

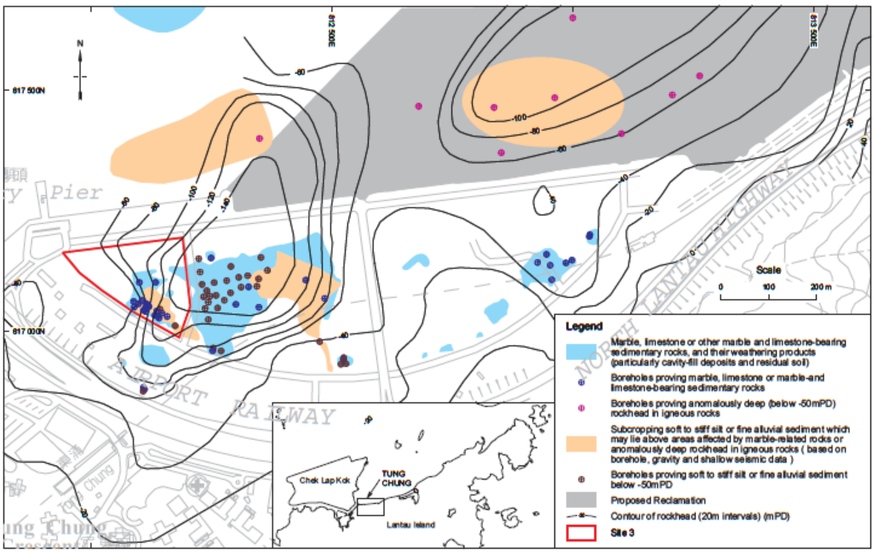

Figure 2: Map showing complex geological conditions in part of Tung Chung East (Sewell & Kirk, 2002).

2 Methodology

The generation and analysis of multi-temporal 3D digital models mainly comprised 4 major works including (1) Generation of historical aerial photographs-derived 3D surface model (non-georeferenced), (2) Generation of LiDAR-derived 3D surface model, (3) Generation of 3D engineering rockhead mesh model, and (4) Georeferencing the historical aerial photographs-derived 3D models.

2.1 Photogrammetry-derived 3D Surface Model

The 3D Digital surface model for years 1963 (Figure 3a), 1993 (Figure 3b), 1998 (Figure 3c), 2000 (Figure 3d), 2001(Figure 3e), 2004 (Figure 3f), and 2020 (photogrammetry) (Figure 3i) were built from historical aerial photographs using the SfM technique. The historical aerial photos were obtained via the online geospatial data provided by the Hong Kong Map Service 2.0 (HKMS 2.0) at a resolution of 300 dpi. A total of 263 aerial photos taken at height from 2800 ft. to 8000 ft., were used in generation of 3D surface models for the seven models. (24 photos for 1963; 38 photos for 1993; 25 photos for 1998; 15 photos for 2000; 39 photos for 2001; 26 photos for 2004; 96 photos for 2020). The models were built in a point cloud format (.las) using the software Agisoft Metashape Pro. To remove point cloud noise from the models, data cleansing is performed by using the "Segment" tool in the software CloudCompare, for better visualization and qualitative analysis in the later stage.

2.2 LiDAR-derived 3D Surface Model

The 3D Digital surface model for years 2010 (Figure 3g) and 2020 (LiDAR) (Figure 3h) were built from the available 2010 and 2020 airborne LiDAR survey data from the Geotechnical Engineering Office (GEO), HKSAR. The "Ground" and "Any first returns" LiDAR data points were selected for building the 2010 model; whereas the "Ground", "Building", and "Vege" LiDAR data points were selected for building the 2020 (LiDAR) model.

2.3 3D Engineering Rockhead Mesh Model

To understand the engineering geological conditions of TCNT, a mesh model of rockhead level (Figure 4) was generated from 514 No. of drillholes by using the ground modelling software Leapfrog Works. The drillhole data were obtained from 43 Geotechnical Information Unit (GIU) ground investigation reports in Geotechnical Information Infrastructure (GInfo). The resolution of the subsurface model was set to 15m. The subsurface model was exported as file type .dxf for further visualization and analysis, together with the 3D surface model, in CloudCompare, ArcGIS Pro, and AutoCAD.

2.4 Georeferencing

Since the historical aerial photographs obtained from HKMS 2.0 were lack of geospatial information, the scale and the coordinate system of the photogrammetry-derived 3D surface models were incorrect. Georeferencing process were performed on all the seven photogrammetry-derived 3D surface model using CloudCompare, with 2020 LiDAR-derived 3D surface model serving as the referencing frame for coordinate point input. They were all projected using Hong Kong 1980 Grid as the coordinate system.

Six points had been selected as ground control points (GCPs) for georeferencing in 1963 models. Due to the lack of man-made infrastructures at that time, the selection of GCPs would mainly focus on picking points of recognizable mountain peaks. Five other points were selected as GCPs for georeferencing in 1993 model. The GCPs selected were mainly focusing on different corners of the newly reclaimed land for better georeferencing quality of the study area.

The selection of GCPs for 1998, 2000, 2001, and 2004 were mainly focus on the man-made infrastructures as more buildings and lands were built and reclaimed since 1998. The GCPs were selected at corners on different high-rise and low-rise buildings. Seventeen GCPs were picked for georeferencing in these four models.

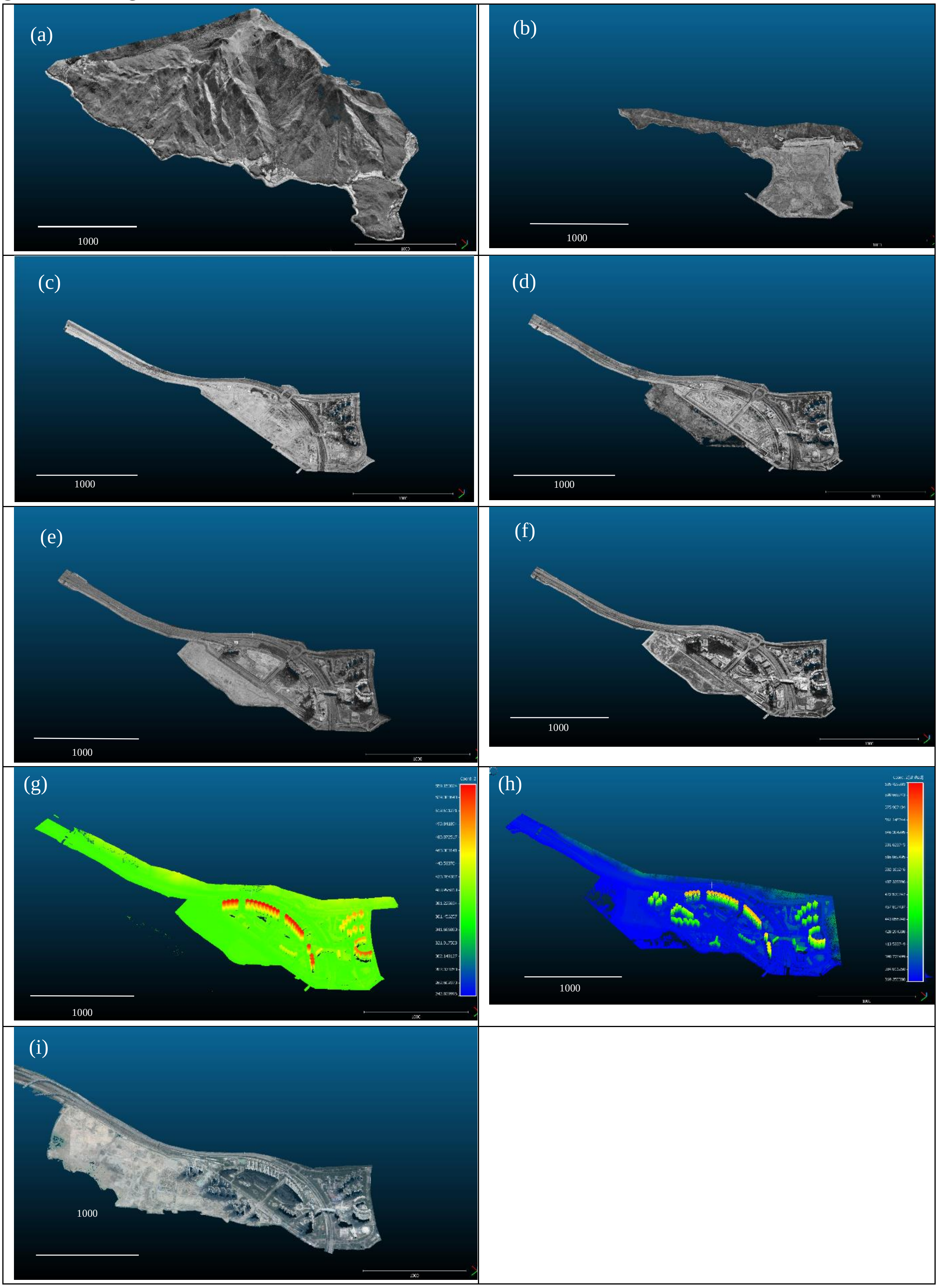

Figure 3: Photogrammetry-derived 3D surface models of (a) 1963; (b) 1993; (c) 1998; (d) 2000; (e) 2001; (f) 2004; (i) 2020; LiDAR-derived 3D surface model of (g) 2010; and (h) 2020.

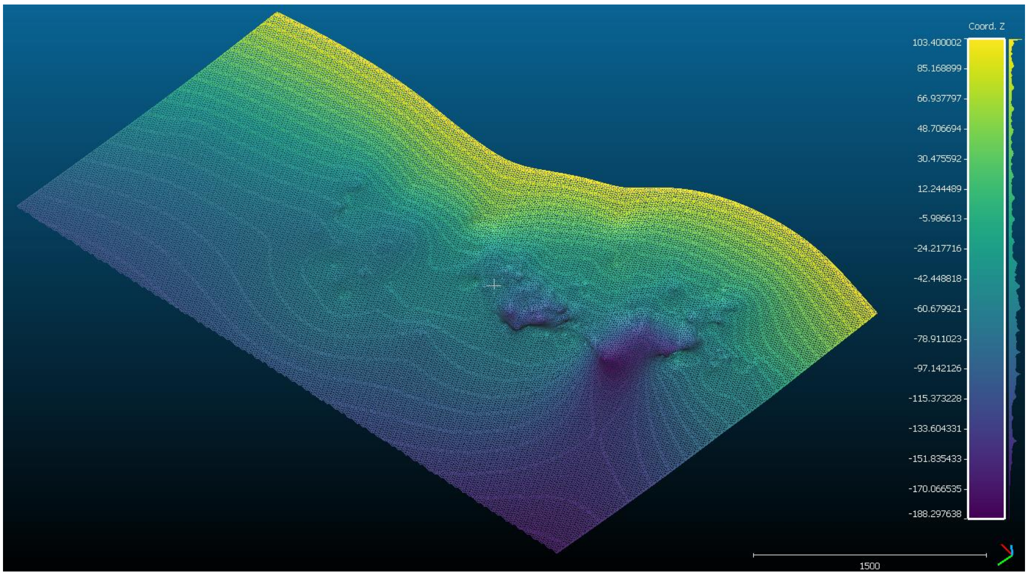

Figure 4: 3D Engineering Rockhead Mesh Model indicating general rock head level of the study area

2.4.1 Georeferencing Quality Assessment

To assess the georeferencing quality of the photogrammetry-derived models, a method called Multiscale Model to Model Cloud Comparison (M3C2) (Lague et al., 2013) was used for 3D direct point cloud comparison of the models. This method could accurately calculate and measure the orthogonal distance between two point clouds, and thus their 3D variations with consideration of cloud roughness.

This method was applied with the use of CloudCompare in computing the mean offset between the georeferenced photogrammetry-derived models and the reference model, i.e. 2020 LiDAR-derived model. For a more accurate assessment on models of early-stage TCNT Development, buildings were filtered out in the 2020 LiDAR model when performing M3C2 with the 1963, 1993, and 1998 models. This is to avoid counting of buildings from 2020 model as offsets on the undeveloped land of 1963, 1993, and 1998 models. The mean offsets for the 1963, 1993, 1998, 2000, 2001, and 2004 models are listed in Table 1.

Table 1: Mean offset of photogrammetry-derived 3D surface model with reference model.

Photogrammetry-derived 3D surface model (year)	Mean Offset (m)
1963	0.440057
1993	0.800728
1998	1.612809
2000	1.354278
2001	0.798643
2004	0.021451

3 Aerial Photograph Interpretation (API)

Aerial Photographs taken from 1963 to 2010 have been reviewed to assess the site development history within the Study Area for verifying the validity of the 4D model in this study. A total of 24 paper copy aerial photographs were acquired from the Lands Department, The Government of HKSAR for assessment. API was completed using digital methods with 6 orthorectified aerial photographs (with scale of 1:13000) retrieved from Geotechnical Information Infrastructure (Ginfo). The key observations from API for the study area from 1963 to 2010 are shown in Table 2.

Table 2: Key observations from API for 1963 to 2010

Year	Observations
1963	• The Study Area essentially comprises sea and coastal area. • Agricultural terraces are evident to the southeast portion of the Study Area.
1993	• Land reclamation works had been conducted for Phase 1 Tung Chung New Town Development to the Southwest of the Study Area. • A footpath had been constructed at the southeastern portion of the Study Area. • Vegetation clearance is observed at the southeastern portion of the Study Area.
2000	• Phase 1 Tung Chung New Town reclaimed land had been formed in the central portion of the Study Area. • Land reclamation works had been conducted for Phase 3 Tung Chung New Town Development in the northern portion of the Study Area. • Tung Chung Waterfront Road had been constructed at the western portion of the Study Area. • Tung Chung MTR station, Tat Tung Footbridge, Tung Chung Crescent, Fu Tung Estate, Yu Tung Court, Fu Tung Plaza, schools, Tung Chung Wan Telephone Exchange, and Tung Chung Sewage Pumping Station had been built at the southern portion of the Study Area. • Ling Liang Church Sau Tak Primary School and Ling Liang Church E Wun Secondary School had been built in the central portion of the Study Area. • Construction works had been conducted for Citygate in the central portion of the Study Area. • North Lantau Highway, Man Tung Road, Yi Tung Road, and Ying Hei Road had been constructed in the central portion of the Study Area. • Construction works had been conducted for Coastal Skyline in the central portion of the Study Area.
2001	• More lands were reclaimed for Phase 3 Tung Chung New Town Development in the northern portion of the Study Area. • Commercial Complex of Coastal Skyline, Man Tung Footbridge, Citygate, Tower 1 to 5 of Coastal Skyline had been built in the central portion of the Study Area. • Site formation works had been conducted for Seaview Crescent, Le Bleu Deux-Coastal Skyline Phase 4, Coastal Skyline Le Bleu House, and Caribbean Coast Phase 2 to 4 in the central portion of the Study Area. • Construction work had been conducted for Caribbean Coast Phase 1 at the eastern portion of the Study Area.
2004	• More lands were reclaimed for Phase 3 Tung Chung New Town Development's reclamation work at the northern portion of the Study Area. • Seaview Crescent Block 1 to 3 had been built at the northwestern portion of the Study Area. • Construction works had been conducted for Seaview Crescent Block 5 at the northwestern portion of the Study Area.
2010	• Phase 3 Tung Chung reclaimed land had been formed with vegetation growth at the northern portion of the Study Area. • Man Tung Road Park, Ngong Ping Cable Car Tung Chung Station, and Tung Chung Swimming Pool had been built at the western portion of the Study Area. • Novotel Citygate Hong Kong Hotel, Tung Chung Man Tung Road Sports Centre, Tung Chung Community Hall, Coastal Skyline Tower 6 and 7, Tung Chung North Pet Garden, Tung Chung North Park, Chinese Herb Garden, Caribbean Coast Phase 1 to 4, Bermuda Park, Ho Yu College, Coastal Skyline Le Bleu house, La Mer Block, Le Bleu Deux-Coastal Skyline, and Orange Zone Park had been built in the central portion of the Study Area.

4 Results and Discussions

The 4D digital surface model illustrating site changes of the study area are presented in Figure 5. To better illustrate the site condition and changes in different years, the surface model of 1963 is used as the background model with models from different years overlayed. Quantitative analyses involving extraction of two cross section profiles are presented in Figure 6.

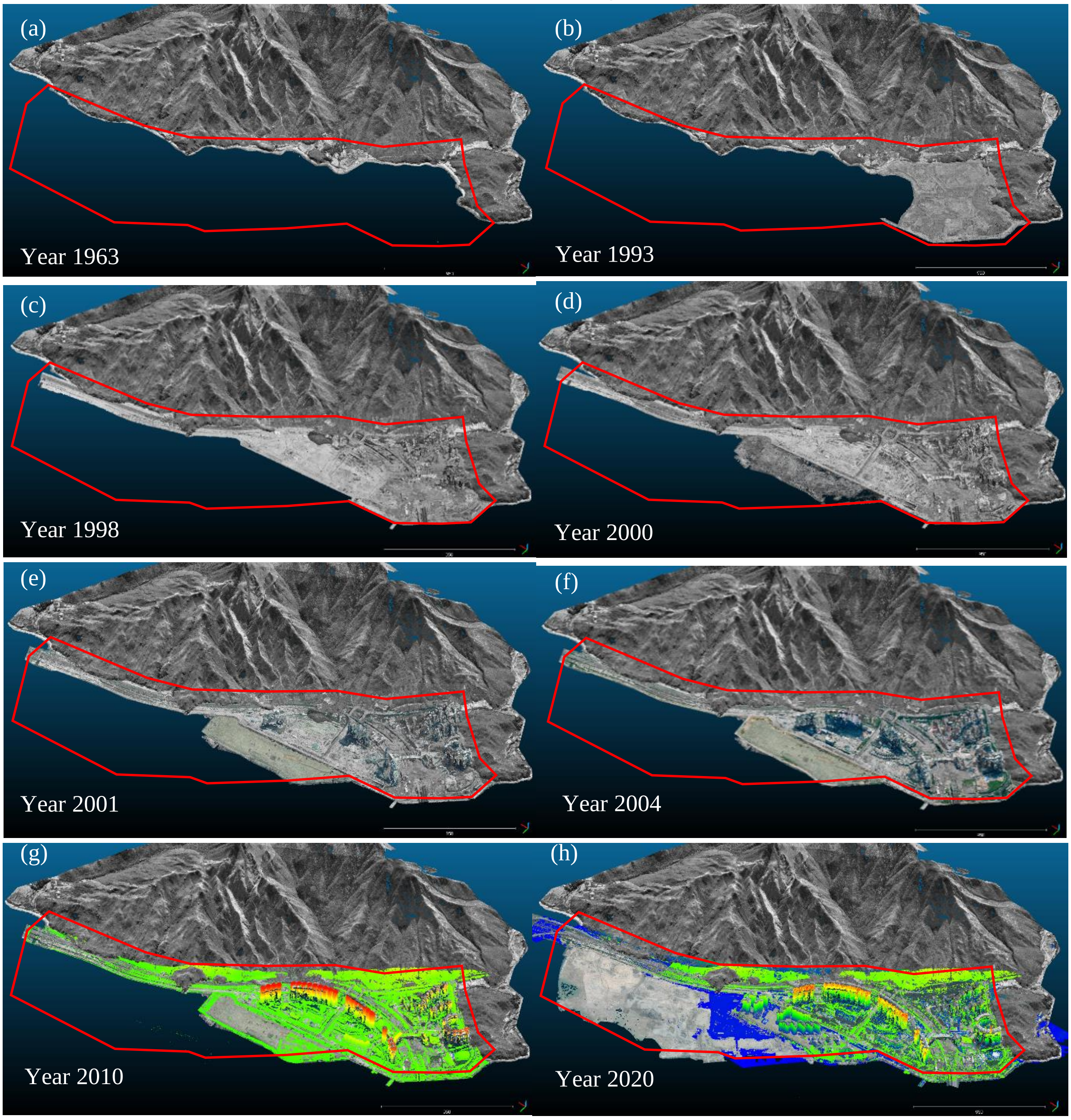

Figure 5: 4D digital surface model illustrating site changes from 1963 to 2020 (Year 1963 model is used as background model with models from different years overlayed). Site conditions in (a) 1963, (b) 1993, (c) 1998, (d) 2000, (e) 2001, (f) 2004, (g) 2010 and (h) 2020. The study area is outlined in red.

4.1 Cross Section Profiles

Two cross sections AA’ (Figure 6b) and BB’ (Figure 6c) were drawn across the study area using ArcGIS Pro. For better illustration, only the years with significant changes in cross section were shown in the profiles. A general comparison between the results obtained from cross section profiles and API are presented in Table 3.

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Table 3: Comparison of results obtained from cross section profiles and API

Cross Section	Results from Cross Section of 4D Digital Surface Model	Results from API
AA' (Figure 6b)	(1) Phase 1 reclaimed land was observed in 1998 (2) Completion of Phase 3 reclaimed land and progressing construction work of Caribbean Coast Phase 4 Crystal Cove Tower 5 between 1998 to 2004 (3) The Coastal Skyline Clubhouse and Caribbean Coast Phase 4 Crystal Cove Tower 5 were built by 2010	(1) Central portion Phase 1 reclamation work was done by 2000. (2) Phase 3 reclamation work was started in 2000, with most of the reclaimed land formed in 2001. (3) Caribbean Coast Phase 4 Crystal Cove Tower 5 was built by 2010
BB' (Figure 6c)	(1) Phase 1 reclamation work was observed in 1993 (2) Completed Phase 1 reclamation, Tung Chung Crescent Clubhouse, Tung Chung Crescent Block 3, and Tat Tung Footbridge were found and built between 1993 to 1998 (3) Phase 3 reclaimed land was formed between 1998 to 2000 (4) Le Bleu House was built between 2000 to 2010 (5) Century Link was built between 2010 and 2020 (6) Progressing reclamation work of Tung Chung West found in 2020	(1) Southwestern part of Phase 1 reclamation work was in progress in 1993. (2) Formation of southeastern part of Phase 1 reclaimed land and completed construction of Tung Chung Crescent and Tat Tung footbridge by 2000 (3) Phase 3 reclamation work had been conducted in 2001. (4) Le Blue House was built between 2004 and 2010. (5) N/A (6) N/A

4.2 Complex Geological Conditions

Complex offshore geological ground conditions including weathered granite and rhyolite featuring some block xenoliths with dissolution features and cavities, was found with highly variable and occasionally extremely deep and steeply inclined rock head levels as illustrated from the 4D digital model. The mean rock head level of the study area is around - 48 mPD, with maximum depth at around -188 mPD. A cross segment is extracted from the 4D digital model (Figure 7) to illustrate the specially planned locations of different buildings and facilities' heights in relations to the rockhead level of the study area. In Figure 7, it is evident that high-rising buildings are present in areas with shallower rockhead levels (at around -40 mPD). In contrast, those areas with the deepest rockhead levels (at around -100 to -188 mPD) contain open areas (i.e., park) without significant structures. The models match the actual situation given the limitations and cost of construction of deep foundations for high-rise buildings in areas with deep rockhead levels and with complex ground conditions.

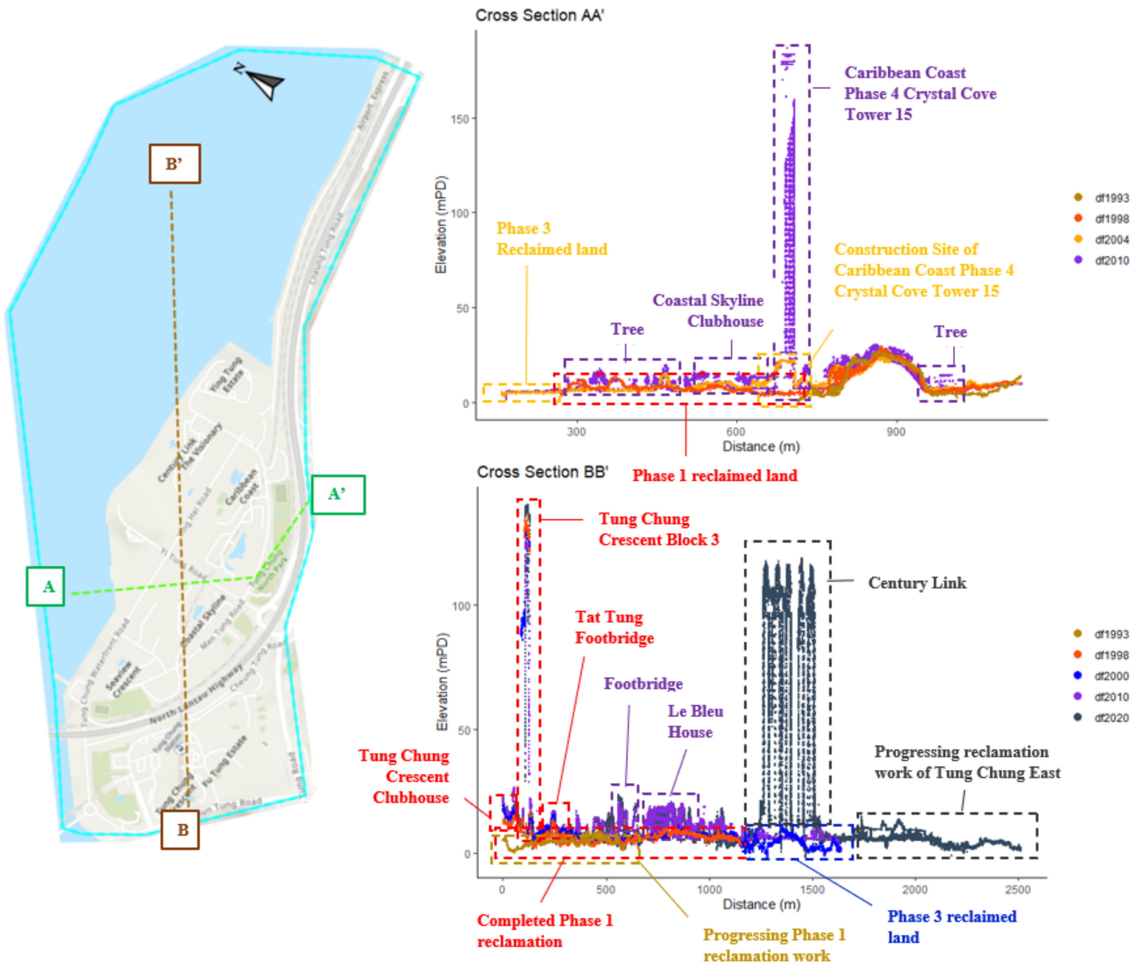

Figure 6: Cross section profiles of the study area. (a) Map showing the locations of cross sections AA' and BB'; (b) Cross section AA' across Tung Chung North; (c) Cross section BB' from Tung Chung Centre to Tung Chung East.

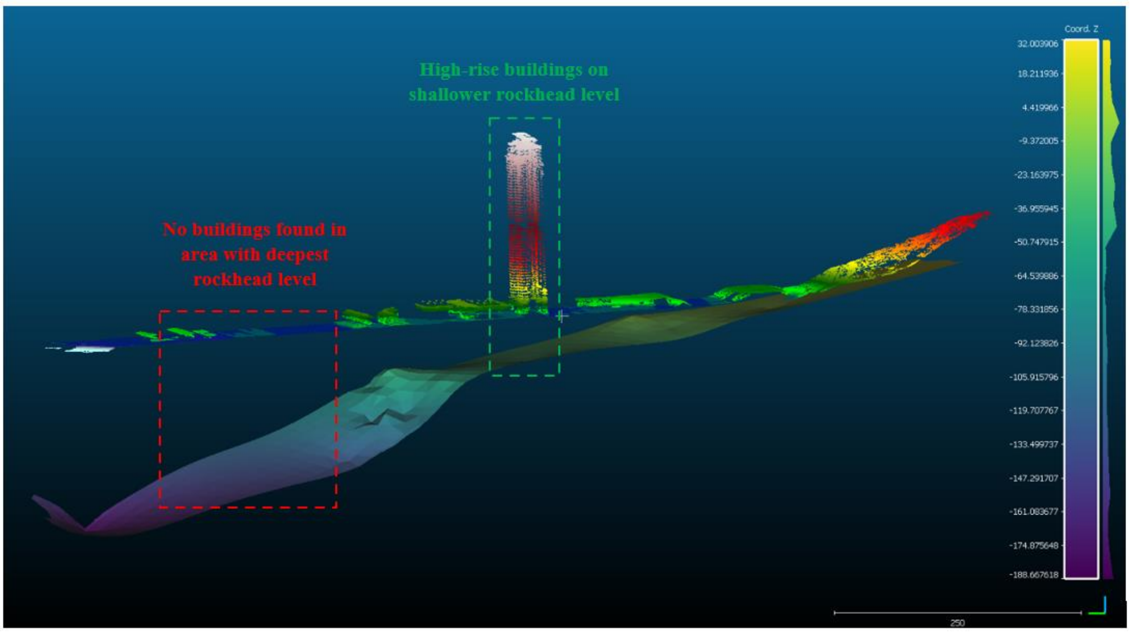

Figure 7: Cross segment of the 2020 surface model with the engineering rockhead model. The colour scale displays the elevation of rockhead level.

4.3 Summary

From the result obtained from the surface model and both the integration of surface and engineering rockhead mesh model, most of the results match with what have been obtained from both API and the literature review. The changes in site conditions including reclamation work and construction of different infrastructures are accurately illustrated and presented from the 4D digital model with its special geological conditions shown. This final result shows that the use of 4D model monitoring method is feasible in monitoring major changes of a site even for prolonged periods.

4.4 Limitations and Suggestions

While the 4D digital model monitoring method described in this paper is feasible in construction monitoring, limitations are found in the model building process in which improvements can be made in future works. Since the historical aerial photographs obtained from HKMS 2.0 in this study were in the format of DAP-L0 version, resolution and geospatial information of the images are limited. The resolution of the images is further reduced with photos taken at high flying heights. Thus, limitations in quality are found in the generation of 3D point cloud surface models using SfM.

In addition, as the digital aerial photos were taken from different months of the same year, the incoherence of features shown in the photos might also affect the completeness in the generation of 3D point cloud surface models. For example, model distortion was encountered in the 2004 surface model, which resulted in incomplete building structure in part of the model. Since geospatial information is also absent from the raw model, further georeferencing is necessary. The missing points in the point cloud model might increase the difficulty in performing geo-referencing manually (GCPs picking), and thus the accuracy and quality of the model.

For future improvements, it is suggested that UE Version of digital aerial photographs can be used for model building. The UE Version of digital aerial photographs are stored in the format of TIFF format with larger range of colour information from 8-bit to 12-bit, and with relevant geospatial information provided (Lands Department, 2021). It is believed that the quality, including resolution and georeferencing accuracy of the model can be greatly improved with the use of UE version of digital aerial photographs. Besides, it is also suggested that digital aerial photographs taken at lower altitudes should be chosen in priority to higher altitudes when generating 3D surface models. This can ensure that more features can be captured and illustrated clearly on 3D models. Aerial photos should also chose with similar shooting date. This is to maintain the coherence of the photos used in model building.

5 Conclusions and Future Uses

The case study shows that the use of the 4D digital model monitoring method is feasible and efficient in monitoring changes in construction site. It could provide a more comprehensive view and allow both qualitative and quantitative analyses of site changes in a systematic way. Cross section profiles can be extracted from the 4D digital model with its elevation change presented clearly. The changes in respective elevations could illustrate the corresponding construction and reclamation works in a given year. These numerical data might be useful in other stage of site planning and keep track of the construction progress and overall site development changes. The use of this smart construction monitoring method could greatly overcome limitations brought by conventional practice of construction monitoring in a more time-efficient and cost-effective manner. It is promising that our innovative 4D digital model and the associated sub-surface engineering rockhead model can be integrated with the Building Information Modelling system at a later stage to constituent a Smart Built Environment and to facilitate a smart construction site monitoring practice in near future.

6 Declarations

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6.2 Publisher's Note

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