Digital Twin for Geotechnical Engineering Applications

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Abstract

Engineers have been motivated to push boundaries and find better tools for a more efficient design process and innovative solutions in construction industry. Digital engineering is the synergistic application of electronic and software technologies. The ultimate goal is to produce digital twins which are digital replicas of real and potential physical assets. With the rise of Building Information Modelling (BIM), digital twin in geotechnical engineering focuses more on the data management. However, the inherent information in digital models can be further exploited for optimizing engineering works. In this paper, this process is illustrated from the viewpoint of geotechnical works. Examples on the use of digital twin to design complex deep excavation and earthwork projects in difficult ground conditions are presented. The geotechnical design process was streamlined and the estimated time saving was up to 50% compared with a traditional design method relying on 2D cross sections. There is also significant time saving for planning of other associated civil elements of works such as master planning as a result of efficient communication and early findings from geotechnical studies attributed to the digital models developed. This was done by combining the use of digital data to produce various models, including Digital Terrain Models and 3D geological models. Besides, innovative monitoring techniques in other case studies are also presented to demonstrate how they assist project stakeholders in monitoring different aspects of a project. The data are readily processed into different formats for monitoring ground movement, monitoring site progress, and controlling excavation and filling works. Overall, digital twin has great potential for geotechnical works.

Keywords: Digital twin, Geotechnical design, Innovation

1 Introduction

Digital twin (DT) has gained popularity and has been gradually adopted in many civil and geotechnical engineering projects. DT encompasses collection of digital data representing physical objects and it can be considered as virtual replicas of physical infrastructures or ground conditions that can be adopted to run simulations before actual works are executed (Lu et al, 2019). Through DT, different stakeholders can visualise, brainstorm, and communicate many different aspects of a project more efficiently.

In recent days, engineers have witnessed increasing complexity in projects combined with tight design and construction programmes. Large projects usually use abundant data from different sources, and these data are transformed to a format that can be used for design and construction. Traditionally, data transformation is carried out manually, involving production of various 2D cross sections and views. These 2D data are then adopted in various analysis and prediction works. This traditional process is also adopted in geotechnical works as illustrated in Figure 1.

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The process is typically hierarchical and tedious. During the design period, design iterations and changes in any component shown in Figure 1 are always inevitable. One can immediately imagine that changes in master layout plan will restart the entire design loop. Such rework will make some processes redundant and certainly induce a heavy cost to the project. On the other hand, demand for efficiency is only increasing rather than decreasing, regardless the situation. In such case, traditional approaches associated with manual data processing may no longer be feasible and new solutions are required.

To ensure successful delivery, streamlined and smooth data handling during design is required. DT has the potential to offer an alternative approach in expediting project execution. With the advancement of computing power and data processing algorithm, abundant data involved in a project can be processed quickly for the benefits of engineering process as early as possible. This paper aims to present a few practical examples to demonstrate the actual benefits of adopting DT in geotechnical works. It is built on two case studies involving design for deep shaft excavation and large-scale earthwork in a seismic region. Subsequently, innovative monitoring techniques used in other case studies are also presented.

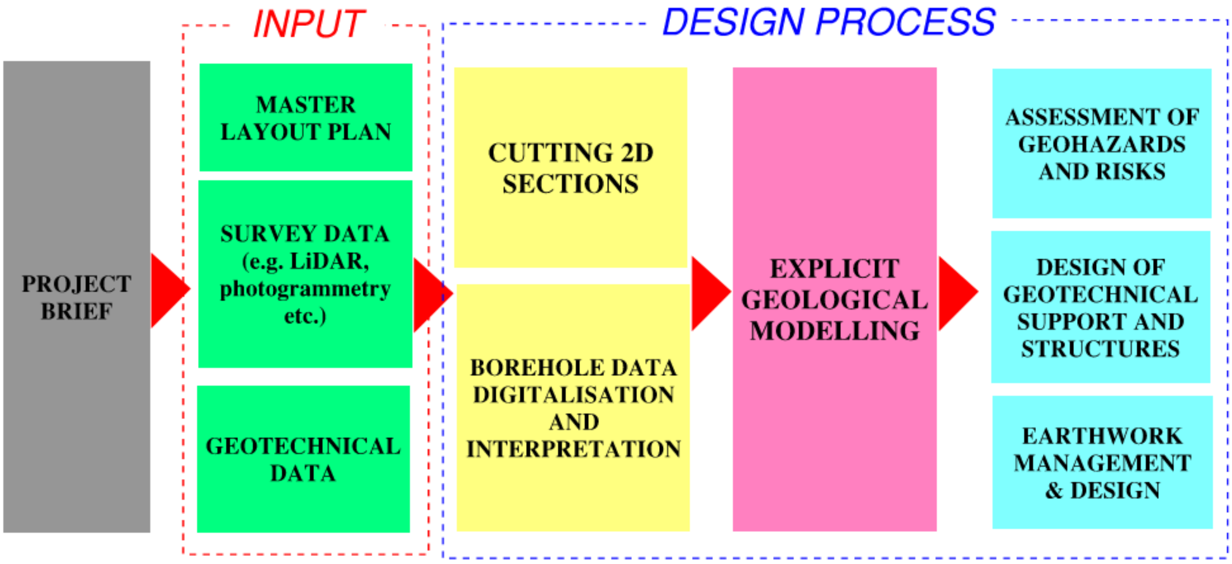

Figure 1: Traditional Design Approach in Geotechnical Works

2 Digital Twin for Design

In geotechnical engineering, DT is adopted to predict and model ground profile in a more organized and accurate manner, compared with traditional methods, and to estimate risks associated with the ground conditions. Examples of DT applications have been demonstrated by Chan et al. (2019) and Mak et al. (2019). DT not only offers data management for ground models and integration with BIM, but also improves design engineering processes.

2.1 Digital Twin for Deep Shaft Excavation

Figure 2 shows a streamlined process from geological modelling to geotechnical analysis stages of a deep shaft excavation project. This example shows the shaft excavation in complex geological conditions. Based on preliminary review of the borehole data, it was identified that the soil layering

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and rockhead were highly non-uniform across the site. Leapfrog was employed to create a representative DT for design and assessment. The modelling process produces rich data, including thickness of various soil materials across the site. The Leapfrog model can be immediately used in other software packages for analysis. Subsequently, some potential effects on design and construction of the shafts arising from the geological conditions can be quickly identified, as follows:

- Due to non-uniform rockhead levels, unbalanced forces in the shaft walls can be expected. By adopting the Leapfrog model in 3D numerical modelling, unbalanced forces can be analysed. Subsequently, the shaft wall thickness and reinforcement can be designed accordingly.
- The situation above also influences dewatering design. Dewatering scheme for each shaft was specifically designed considering the soil units encountered and the rockhead profile.
- Based on the 3D geological model, the contractor can evaluate its construction methodologies, determine excavation sequence of the shafts and adits, and plan for contract programme.

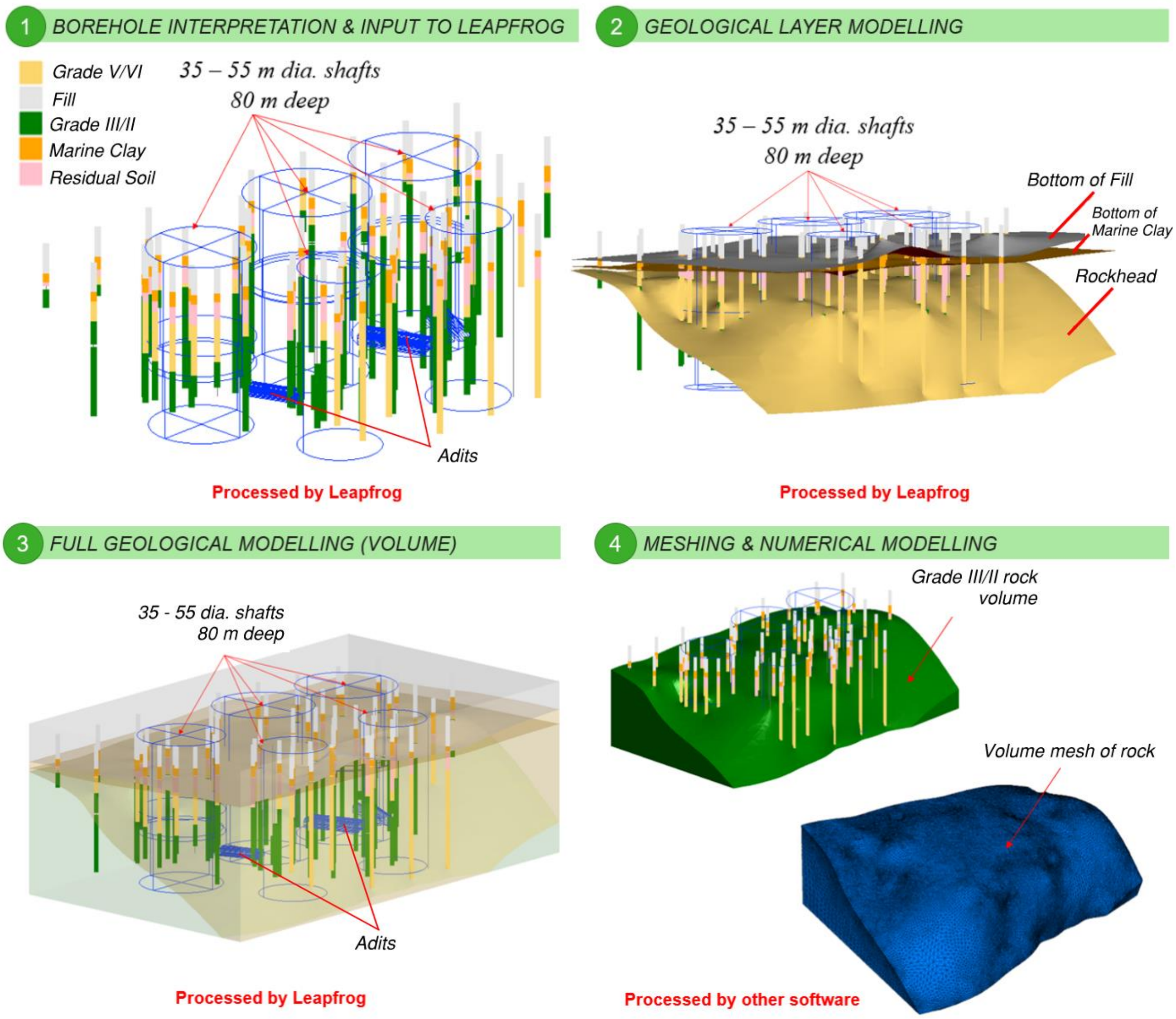

Figure 2: Streamlined Digital Twin Modelling for Deep Shaft Excavation

2.2 Digital Twin for Earthwork

DT is particularly useful when dealing with earthwork in complex terrain with different geological units. Such condition cannot be well handled in the 2D environment. Figure 3 shows a case study of large-scale infrastructure works involving 25.8 million m^3 of earthwork volume in 400-ha land. It was planned for a public transportation hub. The earthwork was required to be finished within a 2-year period and this would be followed by construction of buildings and other structures for full operation two years later. As a result of this tight programme, the period of detailed design for the earthwork was squeezed to only 4 months.

In addition to the challenging timeframe, other challenges arose from its ground conditions. The site was situated in hilly terrain and in seismically active area at the toe of a dormant volcano. Cut and fill works were required, and in different areas the fill thickness or cut depth could reach 30 m (Figure 4). The ground conditions were mainly dominated by weathered tuff. Soft alluvial deposits were identified at some isolated locations, hence the risk of large settlement and differential settlement needs careful consideration. Considering these conditions, the components of detailed design for the earthwork comprise the following:

- Review and optimization of planning for additional ground investigation (GI) works;
- Slope stability analysis and design of slope stabilisation systems;
- Prediction for long term settlement and differential settlement;
- Earthwork management;
- Liquefaction assessment; and
- Ground improvement design.

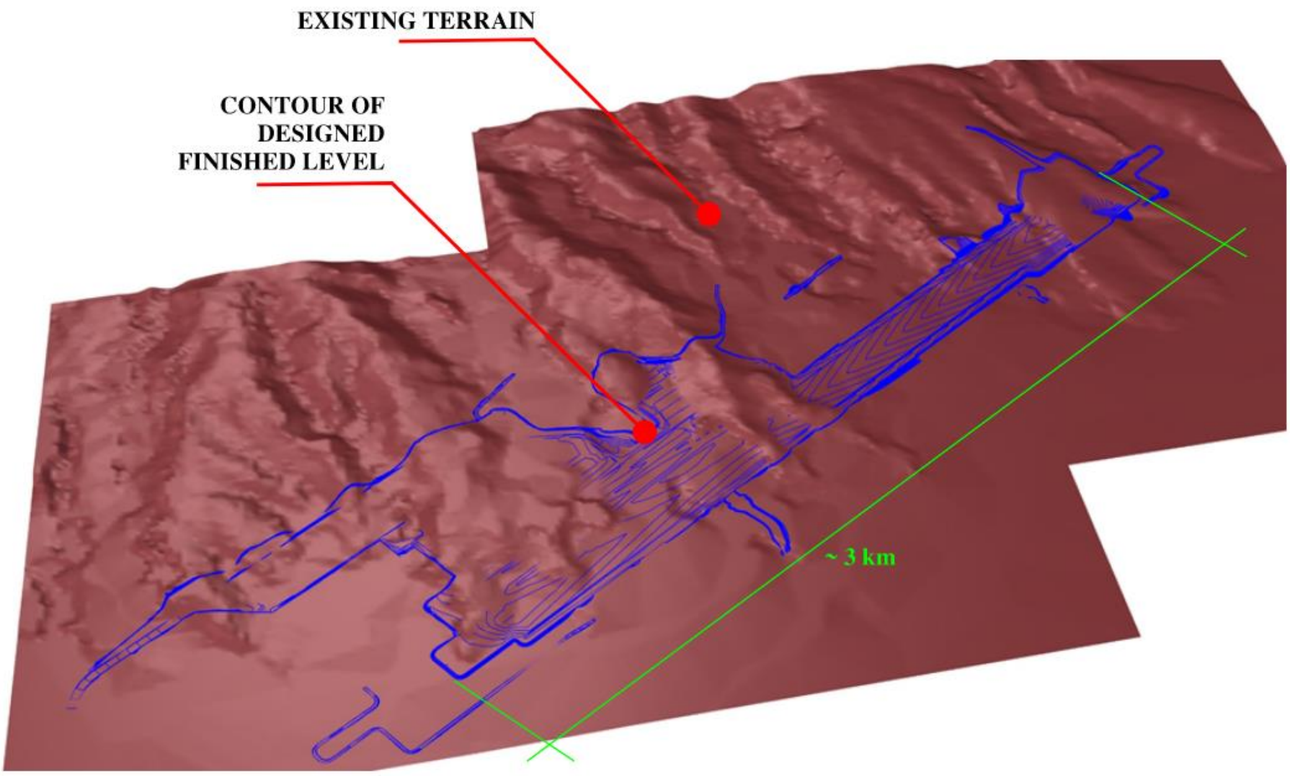

Figure 3: Isometric View of Existing Terrain and Finished Level

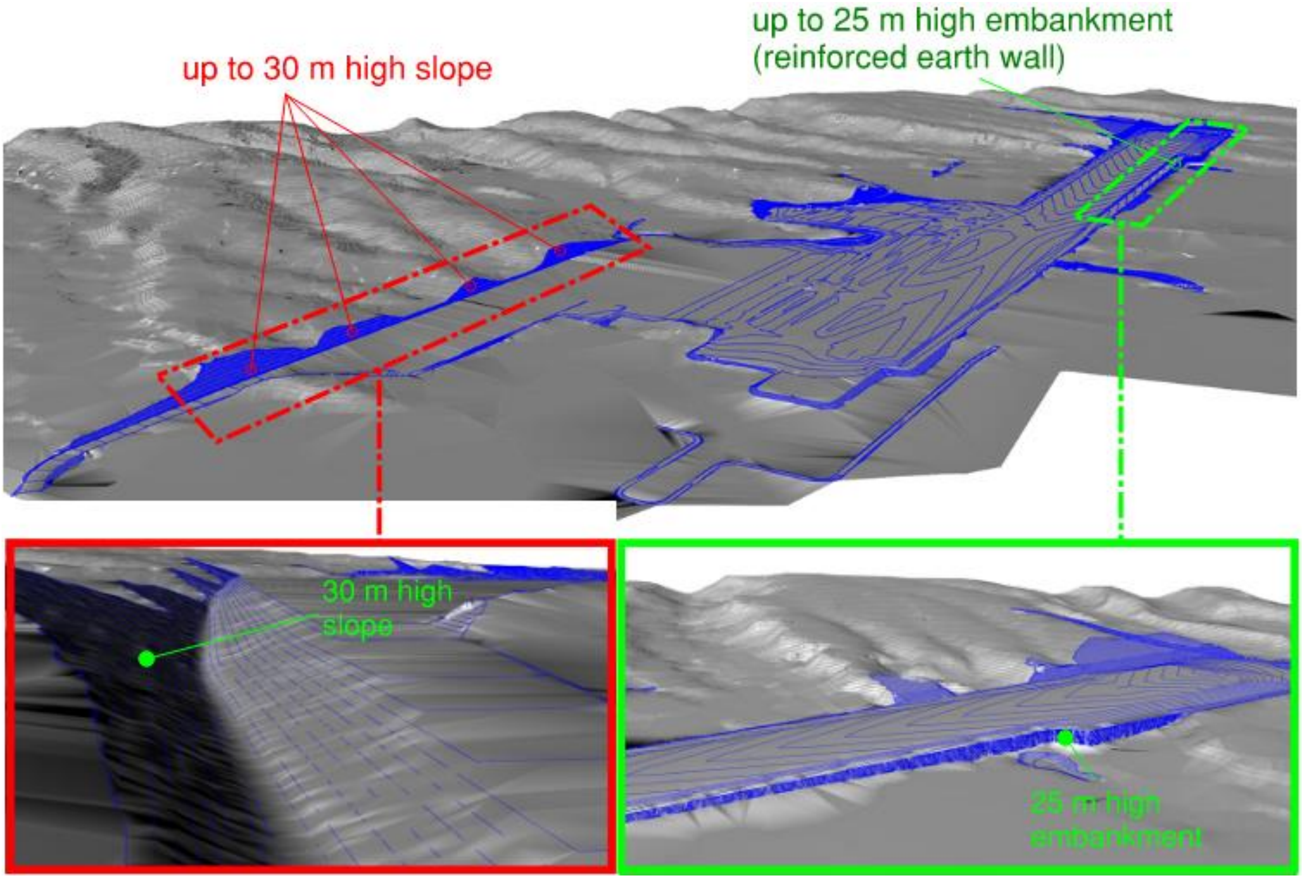

Figure 4: Illustration of Cut Slope and Fill Embankment

For a fast-track, large-scale infrastructure development project of significant geotechnical challenges in a developing country, planning of GI works needs to consider the technical, cost and programme factors. The ground risk could be managed by the digital 3D ground models developed, which are a useful visual tool to inform the project stakeholders of variability and uncertainty in geology across the site. Additional GI could be then focused in the high-risk areas.

During the earthwork design, the master layout plan was still being developed. Hence, iterations were expected in any stage of the earthwork design. This process required a seamless, automated design process overcoming the limitations of traditional approach relying on manual handling using 2D cross sections. A combination of digital terrain modelling, Geographical Information System (GIS) modelling, and implicit geological modelling (Leapfrog) was adopted together with standard geotechnical analysis packages. The key is the interoperability between the different digital platforms. As soon as this runs seamlessly, geotechnical engineers can focus on achieving a robust and optimised geotechnical design which can be incorporated in the development of master layout plan.

2.2.1 Site Reconnaissance and Geotechnical Hazard Assessment

Considering the site area of 400 ha, site reconnaissance was not a trivial task and site visits might not be able to capture a thorough condition of the site. In this situation, utilising digital data such as LiDAR, orthophotos, and borehole data provides an alternative way for site reconnaissance.

Figure 5 shows the orthophoto of the site presenting the complete existing surface conditions. Combined with borehole data, this photo indicates the approximate locations of critical geotechnical features which may affect the design, for example the extent of alluvial plain. This plain is associated with relatively soft deposits and when this area is loaded, it will be subject to long term settlement. This would induce potential problems to the infrastructures in terms of differential settlement due to variability in ground conditions.

The alluvial plain also poses seismic risk, because apart from soft clay it also consists of loose sand. An earthquake could trigger liquefaction that could induce large ground deformation and failure of the adjacent slopes. Figure 6 presents the geological model demarcating the alluvial plains at the site. This knowledge became the basis of settlement predictions, liquefaction assessment, ground improvement design and value engineering, which aimed to resolve any potential stability and serviceability/ground settlement problems during the operational life of the hub.

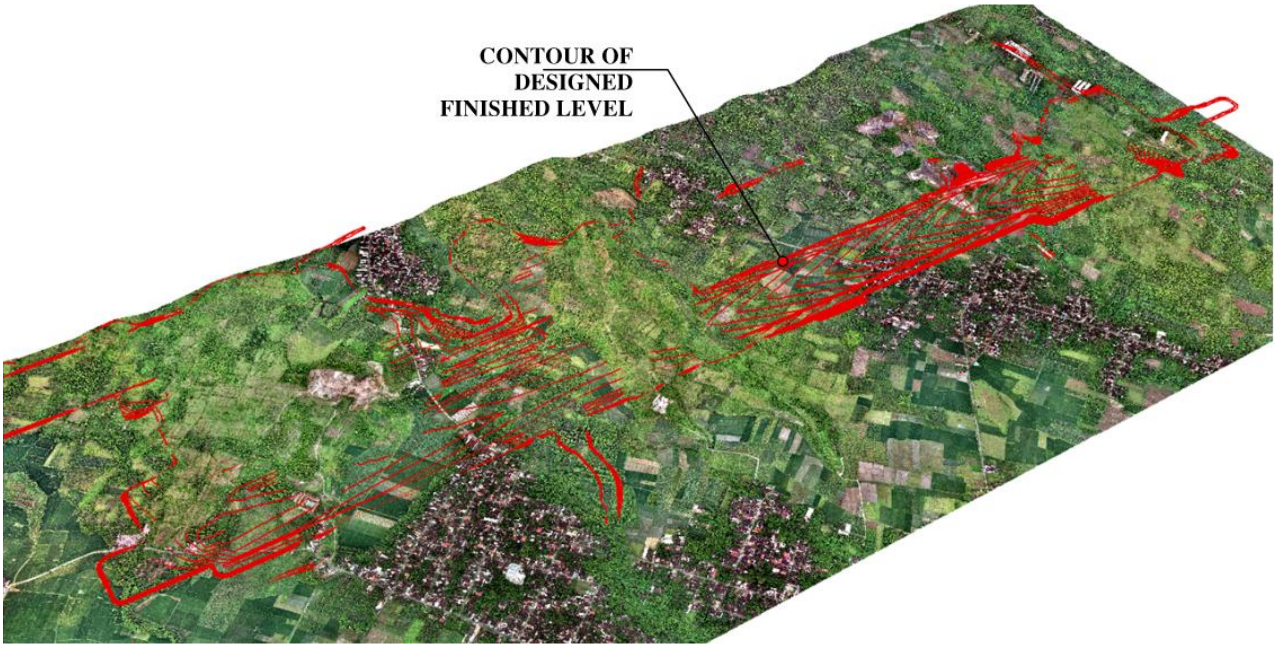

Figure 5: Orthophoto of the Site

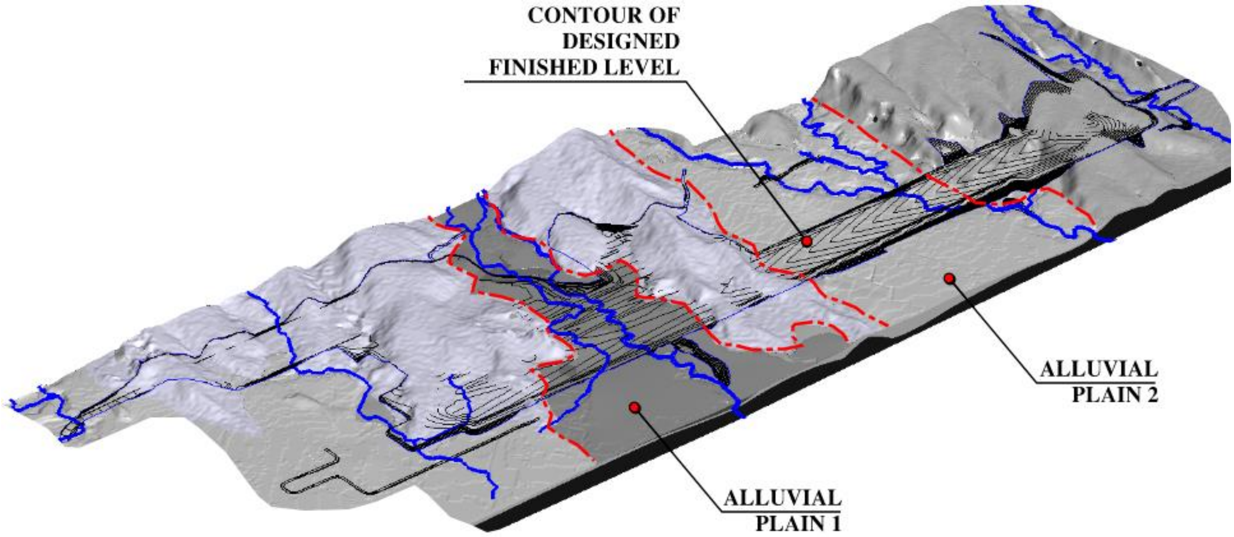

Figure 6: Ground Model with Identified Alluvial Plains

2.2.2 Managing Cut and Fill Balance

The site was in complex terrain. To prepare for a relatively flat grade for the hub, massive cut and fill volumes were required. This was a challenging issue considering limited material sources around the area. The use of sorted material from excavation works within the site was preferred to minimise the use of materials from borrow areas away from the site. Figure 7 shows the significant amounts of cut and fill thicknesses for the site. Figure 8 shows the changes in elevations from the existing conditions to the final grade. Therefore, earthwork sequencing was a critical component in the planning stage for achieving sustainable construction in terms of balancing the cut and fill volumes.

In the analysis of cut and fill thicknesses and volumes, available digital data such as LiDAR data and digital data of the master layout plan have been used. Digital Terrain Models (DTM) was created based on several LiDAR datasets taken in the previous years, and these models were compared with DTM for the final formation level.

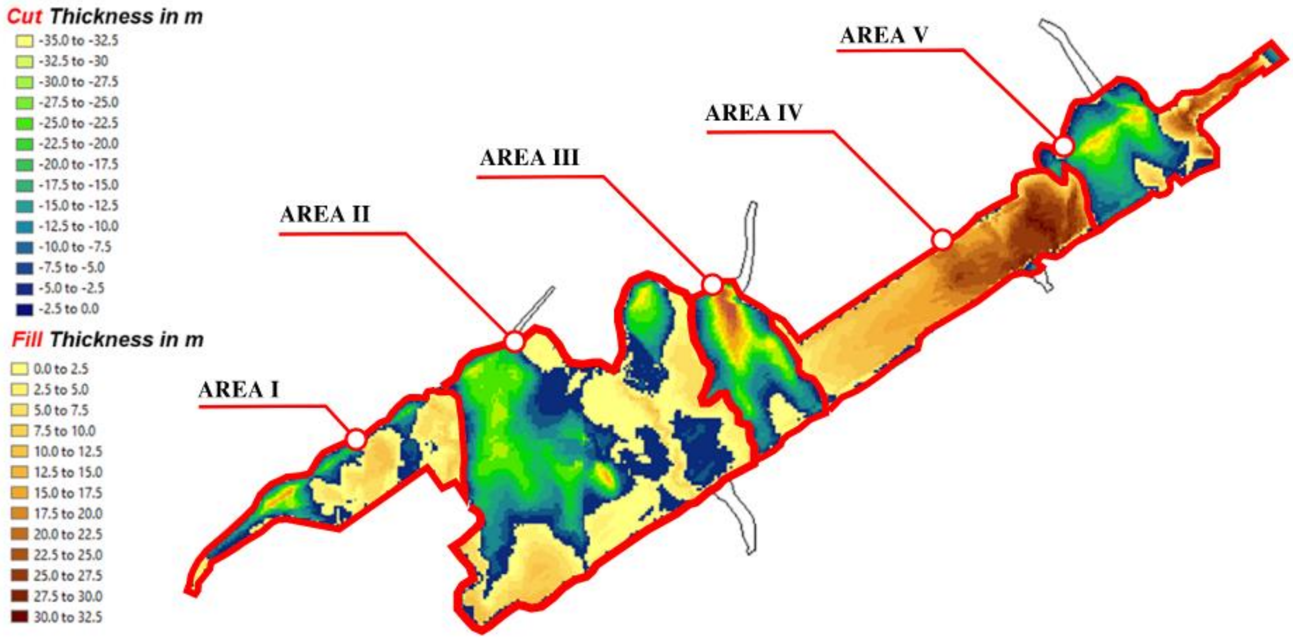

Figure 7: Plan View Showing Works Areas and Cut and Fill Thicknesses

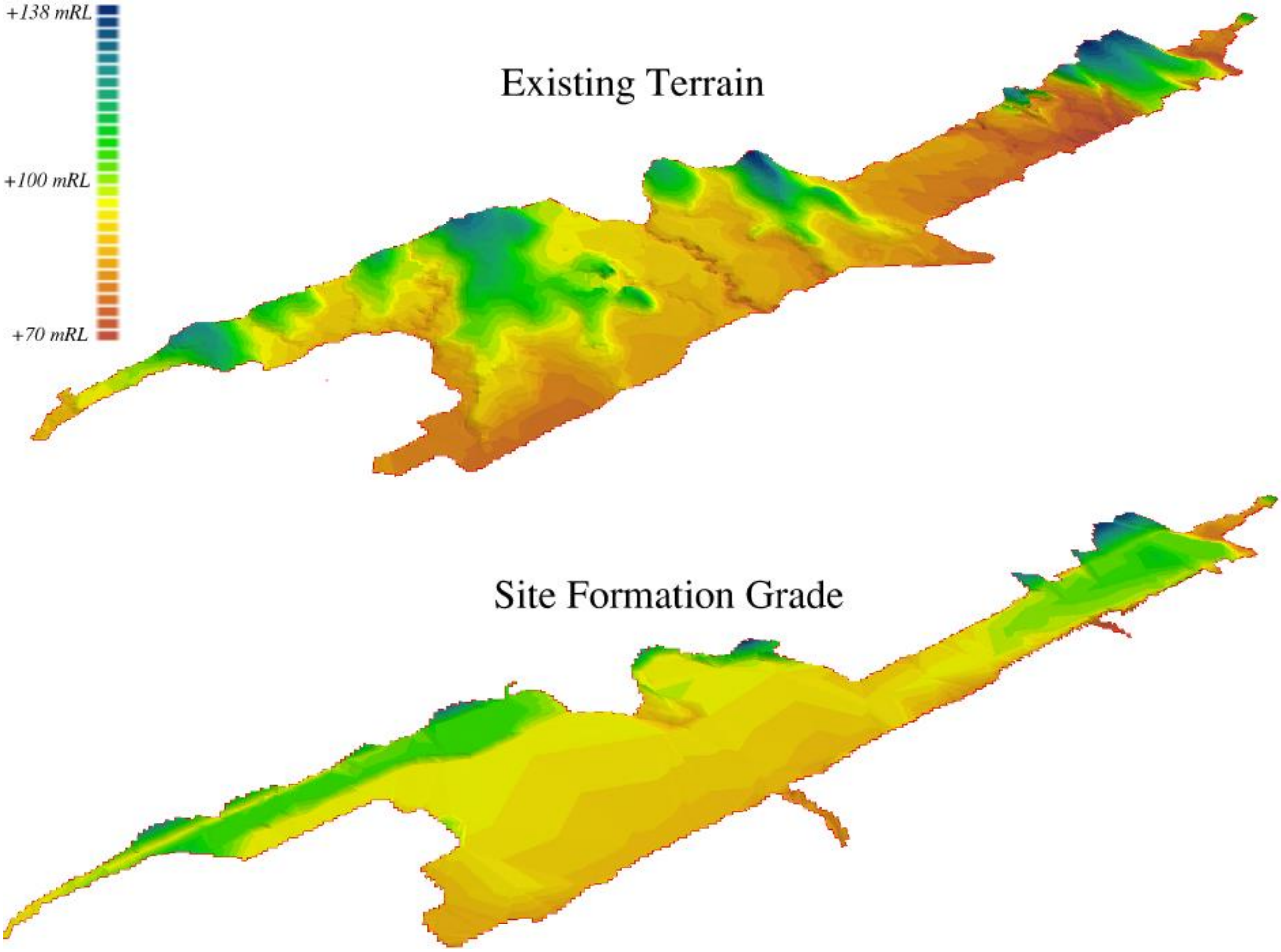

Figure 8: Isometric View of Existing and Site Formation Grades

These results were then combined with the existing 3D ground model data to check the existing material types. Subsequently, assessment of the material characteristics was carried out to determine their suitability as a fill material. Thickness of each material can also be mapped and subsequently, the use of excavated materials available at each area can be optimised. A total cut volume of 13.0 million m^3 and fill volume of 12.8 million m^3 were immediately identified. Table 1 presents the results of cut and fill balance for each area, which are valuable for the contractor to plan its earthwork sequence.

Table 1. Typical Cut & Fill Balance for the Project

Work Area	**Cut Volume [million m^3]**	**Fill Volume [million m^3]**	**Excess Volume (Cut – Fill) [million m^3]**	**Area [ha]**
I	1.0	0.9	0.1	63.7
II	6.1	1.9	4.2	140.8
III	3.1	0.1	3.0	57.2
IV	-	8.7	-8.7	83.7
V	2.8	1.2	1.6	54.6
Total	13.0	12.8	0.2	400

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This process was quickly repeated each time the master layout plan was updated, and the results were communicated immediately to the client and the contractor. For each iteration in the design, the DTM and geological models were integrated directly with the geotechnical design process. Had it been done using the traditional method relying on 2D cross sections, the entire process described above would take longer time and be less accurate. The current integrated process has reduced the time expended on design changes by up to 50%. The digital twin adopted has enabled the geotechnical designer to quickly update the earthwork design for the area as soon as its additional GI is complete. This allows the contractor to immediately commence earthwork in this area, whilst additional GI is still in progress in other areas.

2.3 Digital Twin for Monitoring

Monitoring data is essential to evaluate the performance of the design and construction works. Monitoring works are traditionally carried out using manual systems. For a large-scale site formation works, monitoring works would be labour intensive and time consuming. Surveyors need to travel from one location to another and monitor each individual point (see Figure 9). Even then, the monitoring points are very limited / localised and sometimes inadequate to cover a meaningful area.

Figure 9: Typical Localised Monitoring Point Set Up for Manual Monitoring

With recent technological advances, monitoring works can be undertaken using digital monitoring techniques such as remote sensing technology, e.g. Unmanned Aerial Vehicle (UAV), InSAR, etc. While conventional monitoring instruments only represent localised points and are restricted by site access to install or take monitoring readings, digital monitoring techniques can overcome these two limitations. Moreover, digital monitoring techniques will record abundant data and they can be utilised for different purposes. This section presents some ideas on adopting digital twin in monitoring works.

Figure 10 shows a project site monitored by drones and the acquired photos were processed using photogrammetry techniques. DTM were generated based on the processed drone photos and these provide abundant useful information such as the true coordinates of a location. The use of this technique will benefit many stakeholders as it has capability in monitoring different components of a project. Photogrammetry data can be turned into a DTM and the designer can utilize the DTM in different periods to monitor ground movement of an area (Figure 11). Adopting the same DTM, progress of excavation or stockpiling works can be recorded and used for planning. The contractor or client can turn the monitoring data into 3D imageries such that site activities can be observed in different periods (Figures 10 and 11). The other benefit of taking the digital data is that the information can stored more easily and extracted quickly when they are required.

Other than capturing and building 3D imageries for monitoring the physical conditions of a site, UAV can also be used to monitor geo-environmental events, such as methane gas escaped from a landfill or rising temperature from an activity. A thermal camera or inlet nozzle (for gas) can be mounted on UAV to monitor temperature or surface emission. Figure 12 shows the monitored temperatures of a project site due to mudflow erupting from a gas well with an affected area of approximately 1 km^2. The temperatures were monitored using a thermal camera mounted on a helicopter. The use of this remote sensing technique reduces health and safety risks to engineers when carrying out such difficulty duty. The same approach can be carried out for surface emission monitoring, e.g., gas emitted from a landfill or toxic gas in sewers.

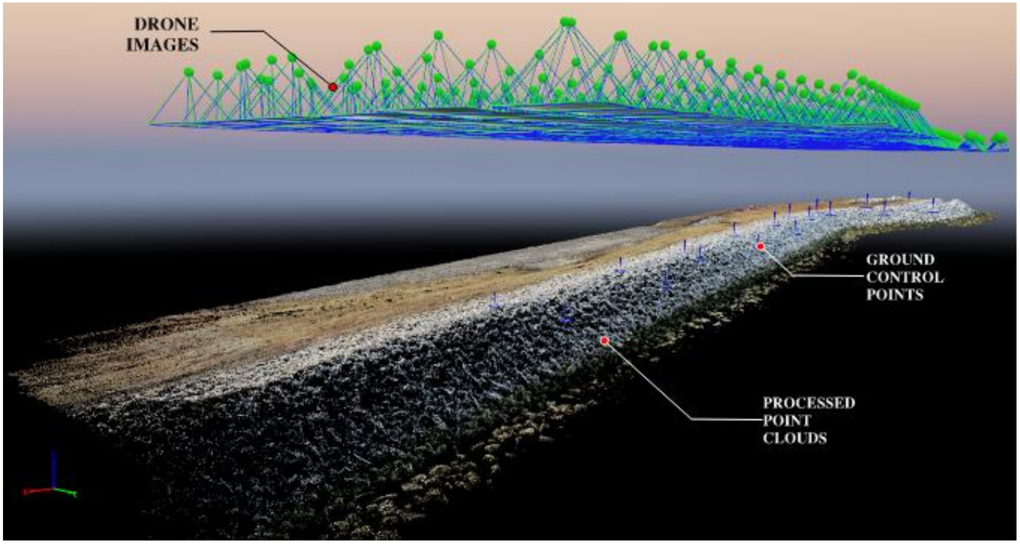

Figure 10: Photogrammetry Processing of Monitored Area (Above) and Constructed 3D Imagery (Below)

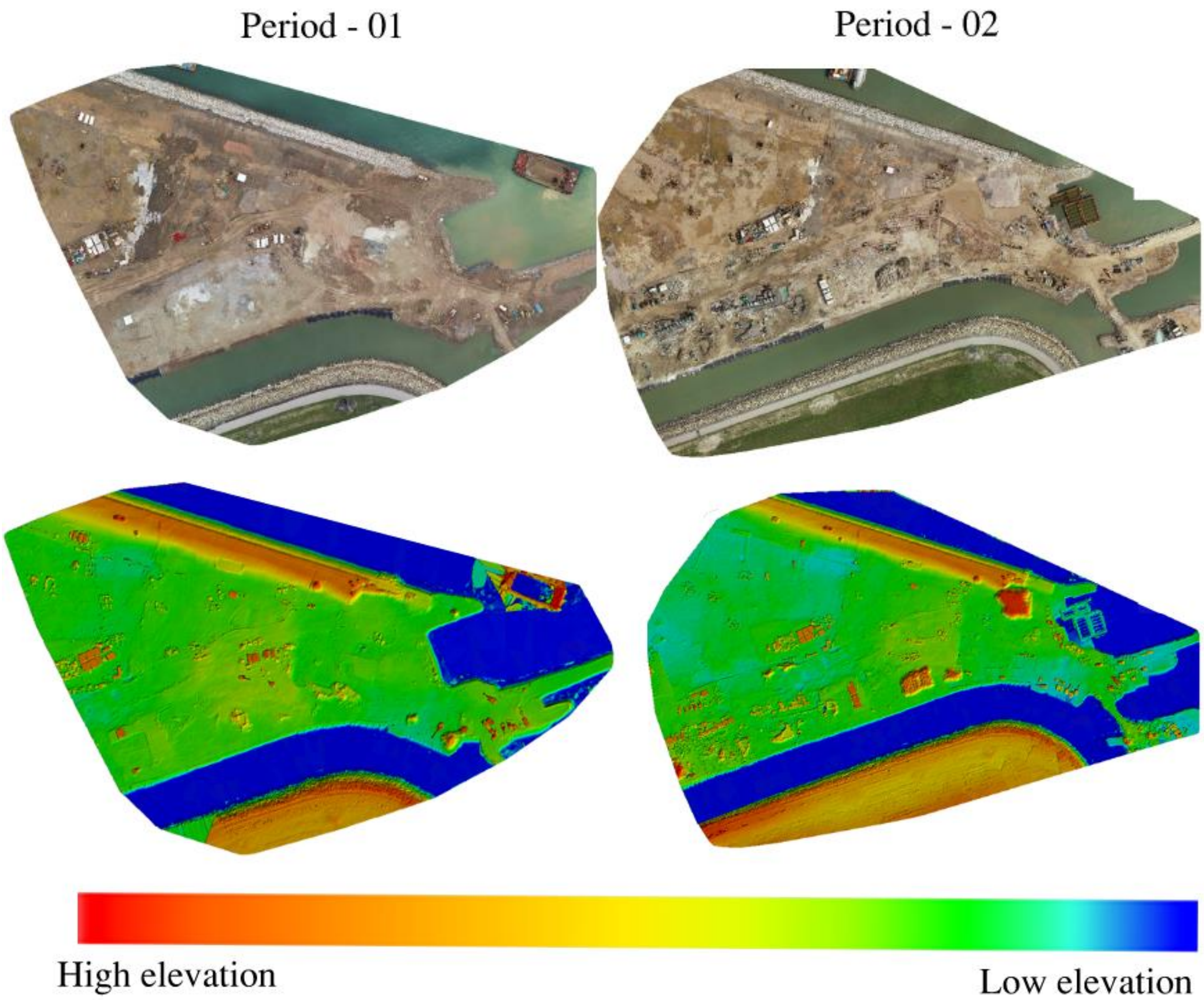

Figure 11: Plan View of Monitored Elevations by Photogrammetry: Orthophotos (Above) and Digital Elevation (Below)

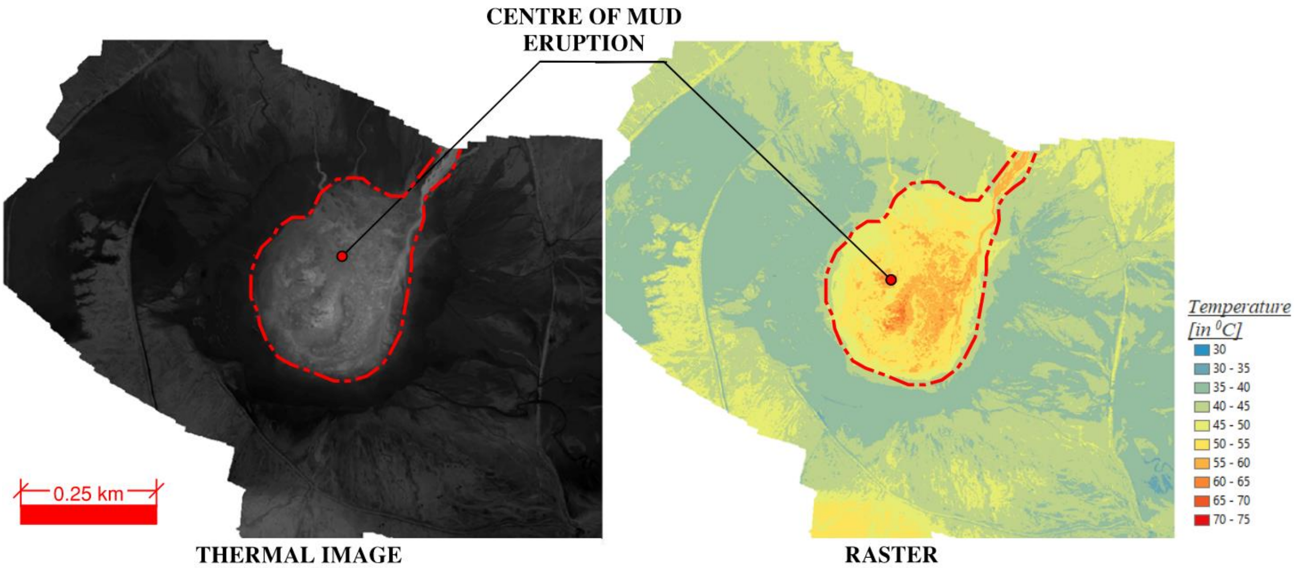

Figure 12: Plan View of Monitored Temperatures of Mudflow from a Gas Well

3 Conclusion

Digital twin (DT) is bringing huge potential to the planning, design, construction, monitoring and maintenance of large-scale, complicated civil and geotechnical projects. This paper has used four case studies to demonstrate the benefits of DT in different project phases to the project stakeholders in terms of improving the efficiency of design process, handling of processing, presentation, and storage of a large amount of information, control and monitoring of construction activities, achievement of sustainable construction, and safeguarding the health, welfare and safety of construction personnel.

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