A Complete Digital Solution to Site Formation, ELS System and Foundations Design

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ABSTRACT

Conventionally, geotechnical designs are carried out on a few representative critical sections. It is probably due to its simplicity as everything is kept in the two-dimensional manner. On the one hand, this approach has been proven to be satisfactory from engineering performance perspective. On the other hand, this approach might have hindered a cost-saving design optimisation. With the increasing computational power as well as growing trend to embrace digital transformation, BIM adoption and design automation, more digital solutions/tools are available in the market. This has opened the gate for a holistic review for design optimisation.

This paper presents some more efficient digital solutions applicable to common geotechnical designs with the help of a few design examples as demonstration. The information flow from planning, design, engineering analysis and drawings preparation is discussed. In particular, the authors focus on how issues of compatibility and interoperability among various digital solutions, which has long been an obstacle for seamless and efficient design workflow, could be resolved.

Keywords: Digital solutions, Geotechnical designs, Automation

1 Introduction

1.1 Background

In coherent with the final call for Net Zero Carbon Emissions in the 27th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27) held in November 2022, the need for a complete digital solution to various geotechnical design, including site formation, Excavation and Lateral Support (ELS) system and foundations, is overwhelming as this could facilitate a systemic optimisation of the design scheme and therefore reduce the emissions of greenhouse gases from the perspective of materials consumption and construction programming. It is expected that such savings could be enormous for mega civil engineering projects in Hong Kong's near future.

Site formation design is the process of preparing land supply suitable for development by shaping and levelling the ground. Key elements in site formation design include design of optimal site layout for the built asset as well as designing the grading and drainage systems to ensure proper water flow and prevent erosion. A well-designed site could reduce the risk of damage or failure and facilitate efficient use of resources for environmental-friendliness and sustainability. In addition, it adds value to the project by maximising the use of available space and optimising the functionality of the infrastructure.

ELS system design involves excavation in soil or rock to create the space for development. It involves the design of a support system that prevents sides of the excavation from collapsing or moving excessively, which causes safety hazards and damage to adjacent buildings and structures. This involves determining the size and shape of the excavation, as well as the depth and slope of the sides and selecting the appropriate support system, which typically includes pile walls, shoring and/or bracing. A poorly designed or constructed excavation could lead to safety hazards, structural damage, and undesirable project delays and, therefore an ELS system design is usually a crucial element in civil engineering projects.

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Foundation design is another critical element of civil engineering projects involving the construction of built assets such as buildings, bridges, highways, and other infrastructures. It involves the design of a stable supporting system counteracting the weight of the built asset and resisting other external forces such as wind, earthquakes and soil pressure. In particular, selecting an appropriate foundation type, which could be shallow foundations such as spread footings or mat foundations, or deep foundations such as piles or barrette, is the prime objective in foundation design. This continues with determining the size and shape of the foundation, as well as the depth and strength required to support the built asset. A well-designed foundation ensures the safety, stability and serviceability of the built asset and prevents undesirable structural damage and unnecessary repairs in future.

In the past few years, digital transformation has been proven to help in many ways in civil engineering projects, including site formation, ELS system and foundations design. For example, digital transformation has helped to improved accuracy and efficiency of the design with digital technologies such as BIM software, digital models, and other simulation tools. These technologies help engineers to visualise and analyse complex data and scenarios, enable them to make more informed decisions and optimise designs. In addition, it enhances collaboration and facilitates communication among project stakeholders, including designers, contractors, and clients, which, in turn, helps streamline the design and construction process, reducing the risk of errors and delays. Moreover, cost savings could be done with digital transformation, which helps reduce costs in civil engineering projects by improving efficiency, reducing errors, and optimising designs.

Overall, digital transformation plays a significant role in improving the efficiency, safety, and sustainability of civil engineering projects. By leveraging digital technologies, engineers could make better-informed decisions, reduce risks and costs, and enhance the overall success of the project. The digital solutions presented in this paper mainly focus on improving design efficiency and quality of design works, which, in turns, enable better design optioneering and reducing wastage due to design errors.

1.2 Objectives

This paper presents some recently developed digital workflows which are applicable to site formations, ELS system and foundations design. These workflows often involve designs and visualisation in the three-dimensional space contrary to the traditional two-dimensional sections, bringing about numerous advantages to the efficiency and effectiveness of the design process. First, design changes, which are inevitable in almost all engineering design journeys, could be more efficiently incorporated into the digital workflows. Second and more importantly, engineering designs carried out in the three-dimensional space would offer a more promising design optimisation, which answer the need for net zero carbon emissions via the use of less construction materials and thus the reduction of construction wastes and energy consumptions, without compromising the safety margin of the engineering designs. Due to limitation of this paper, only the three major geotechnical designs, namely site formations, ELS system and foundations design, will be discussed.

2 Site Formations Design

2.1 Conventional Design Approach

Conventional site formations design is usually done in a sequential approach, where engineering geologists and geotechnical engineers appraise the ground conditions and site constraints, prepare conceptual and/or schematic design for the key built assets, carry out detailed design to determine the extent of slopes and retaining structures to be formed and consider other provisions for the site (e.g., slope furniture, drainage, maintenance access, etc.). By assessing the existing ground conditions of the site, critical locations will be identified for different zones of the site. Design on the slopes and retaining structures could then be carried out based on two-dimensional sections at these critical locations.

2.2 Problem Statement

Commonly in site formation design, the most difficult task is to determine the location and extent of slopes and retaining structures to be formed in consideration of the topography and subsurface ground conditions of the site, which requires accurate interpretation of subsurface ground conditions by the engineering geologist. Ideally, with sufficient ground investigation coverage within the site, ground conditions could be interpreted for the construction of ground models and site formation design could be carried out according to the two-dimensional representative sections at critical locations. However, it is not always the case as existing ground information is insufficient to build an accurate ground model. When the interaction with existing topography comes into the design works, it appears that the adoption of representative sections might only well answer the question of stability of the slopes and/or retaining structures but when it comes to the designed extent of slopes and/or retaining structures, the combination of topography and subsurface ground conditions might make it difficult to determine, especially for site where natural terrain is involved due the complex configuration of the ground profile. In some more extreme cases where soil-rock interface is encountered, determination of slope extent might be even more time-consuming as the design slope angle of the formed slope might not be the same for soil slopes and rock slopes.

Moreover, as site formation is designed to address various constraints such as required formation level, road alignment, site issues etc., the sequential design process would need to be repeated each time when theses constraints are changed or updated. This often lengthens the time required to deliver a design in its final form.

2.3 Digital Solutions

2.3.1 Computation Design with 3D Terrain Models and 3D Ground Models

With increasing computing power and the government's policy of open data for smart city, territory-wide LiDAR data could be used to generate three-dimensional terrain model, as shown in Figure 1, to facilitate the site formation design. From the large amount of information obtained from ground investigation and laboratory tests, three-dimensional ground model could be generated with simulation tools such as Leapfrog, represented in Figure 2, to allow better interpretation and representation of the ground conditions with these geological information visualised in three-dimensional space.

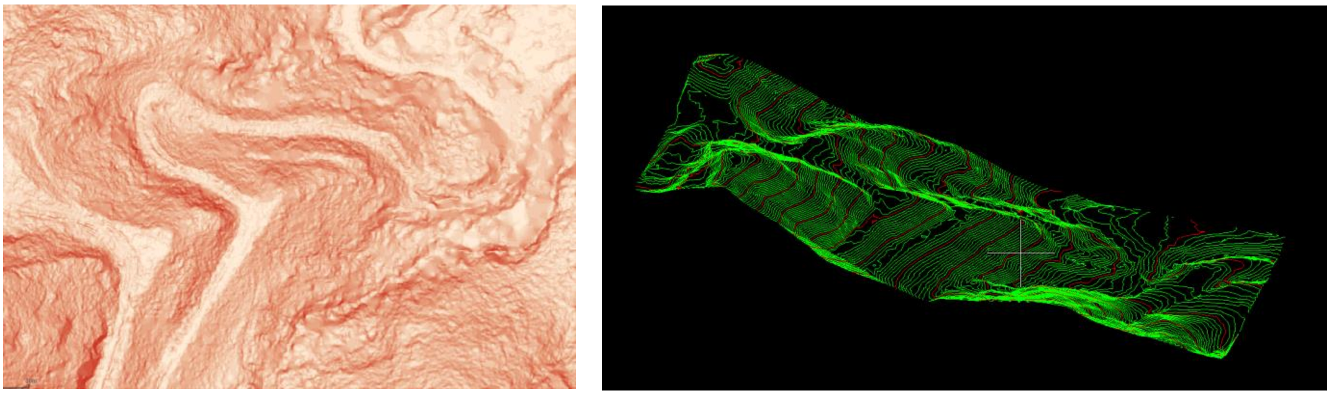

Figure 1: *3D terrain model generated from LiDAR data.*

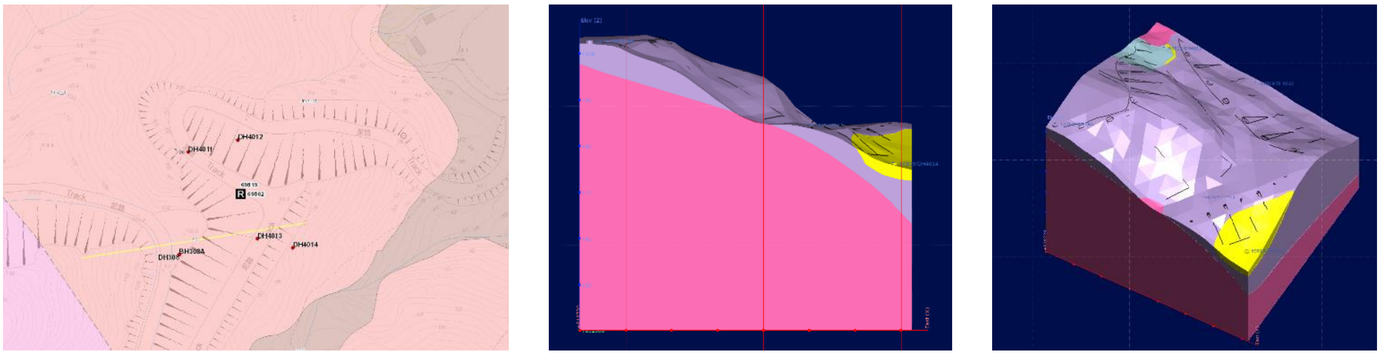

Figure 2: *3D ground models generated from interpreted ground conditions in Leapfrog*

Based on the three-dimensional terrain model generated, together with the footprint or alignment of the built asset, level difference between the existing ground level and desired formation level could be obtained from the software straightforwardly. From this site formation model, design works for slopes, retaining walls and other provisions are made more precisely with ease (GEO, 1984, 1993). Furthermore, compared to the conventional design approach where most of the design are performed only on several critical sections, higher level of design optimisation could be carried out using this model, reducing the repetitive labour intensity when site constraints and design requirements are updated or changed.

Similarly, three-dimensional ground model could now be generated with the interpreted ground conditions and be readily used in association with other BIM software which could build up the slope using "templates". The "templates" is a set of customised design criteria that make use of the information from the terrain models and ground models to generate the required slopes. With proper "templates" defining the required slope angle in soil and in rock, an accurate extent of slope could be generated without much effort compared to conventional design approach where manual interpretation is done exhaustively section by section. An example of computational design workflow using OpenRoads Designer is shown in Figure 3 below.

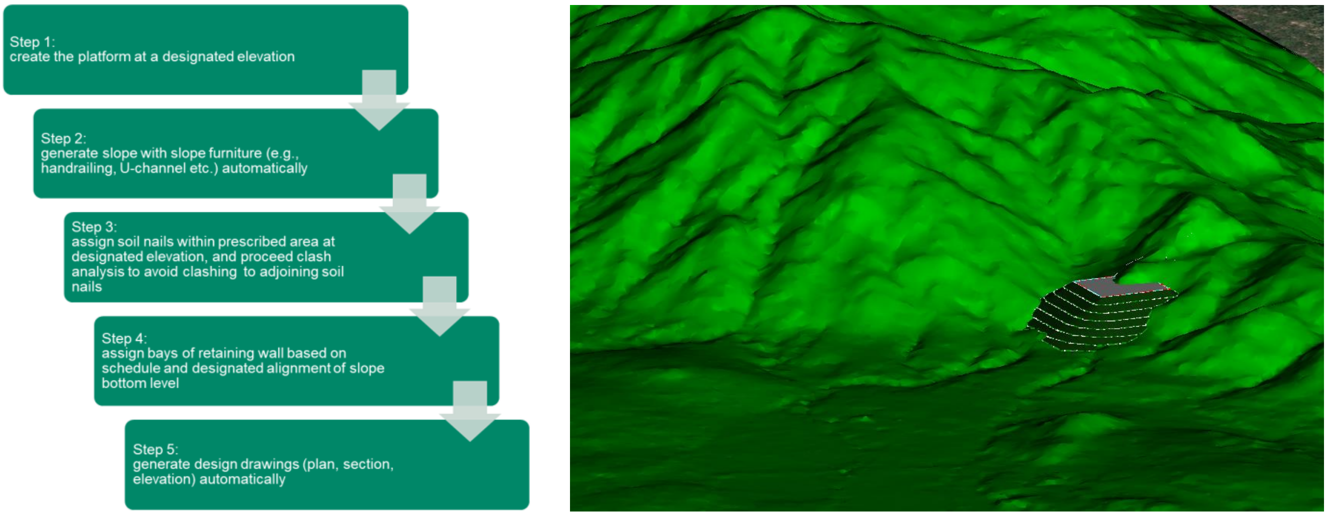

Figure 3: *Site formation design using 3D terrain models and ground models in OpenRoads*

2.3.2 Parametric Design of Other Provisions

Digital tools with three-dimensional site modelling could also be used in the designs of some other relevant provisions. For instance, with the slope stability assessment based on the representative design sections, the required soil nails could be directly generated from the results of the slope stability assessment and be "placed" on the slope in the digital model with corresponding length, orientation and inclination as specified. Alternatively, in some more complex terrain models where local adjustment is required, we can modify the soil nail layout to the designated location which make more sense and re-generate the digital model of the soil nails based on the coordinates of the soil nails in the revised layout (see Figure 4). Clash analysis could thus be carried out efficiently from the model to check if there is any conflicts with other soil nails, underground utilities and/or building and strcutures (GEO, 2008). For any subsequent update on the future ground profile or other design requirements, taking advantage of digital models, soil nails could be redistributed in the software swiftly without the need of intensive and time-consuming labour works.

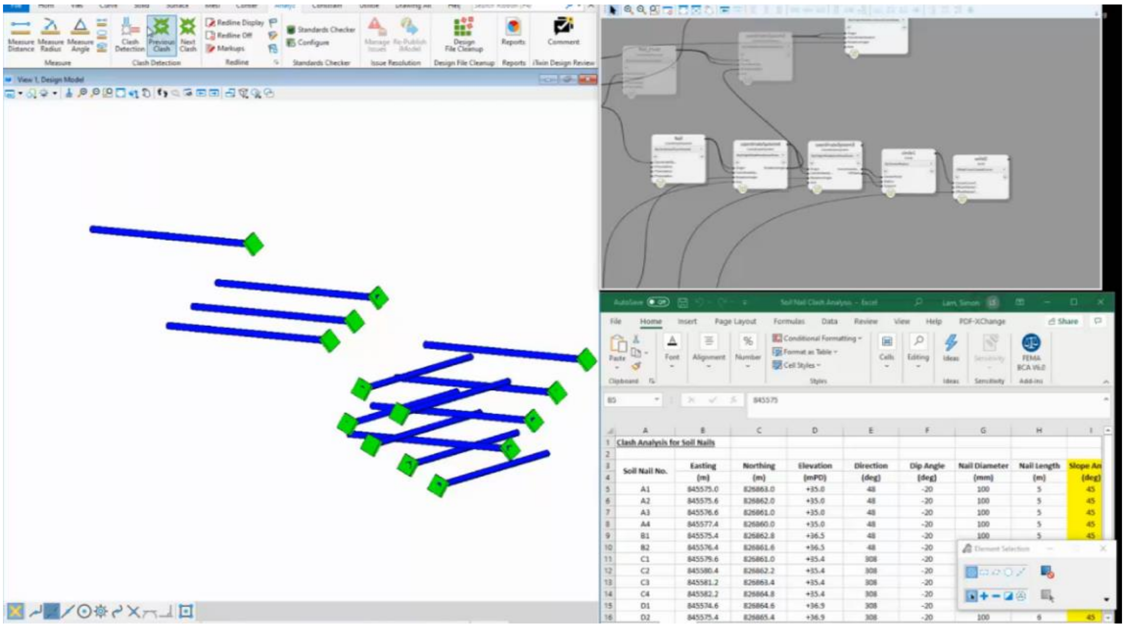

Figure 4: *Constructing soil nails in digital models using OpenRoads Generative Components*

The power of this digital tools is not only confined to constructing soil nails; with proper design of the algorithm, parametric design for other provision including maintenance access and drainage (using size and type of drainage as an input) could also be allowed, greatly reducing the processing time especially for large scale projects.

2.3.3 Quantitative Design Optimisation

One of the major benefits in adopting BIM software is that making use of the digial models and parametric modelling, designers could quickly work out different design options and evaluate their impact on the overall performance. It is also able to couple with other energy analysis tools to evaluate energy consumption and identify area of improvement in great details. Cost estimation could also be generated for various design options with schedules and summaries obtained from the digital models (see Figure 5). Not only the cost could be estimated, materials optimisation by analysing the geometry and structural requirements allows designers to identify opportunities to reduce material waste and minimise the environmental impact of construction. Overall, the digital models help designers optimise the designs by providing quantitative information they need to make informed decisions to assess the

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cost, environmental impact and other performance indicators that could justify the preferred option, quantitatively over intuitively.

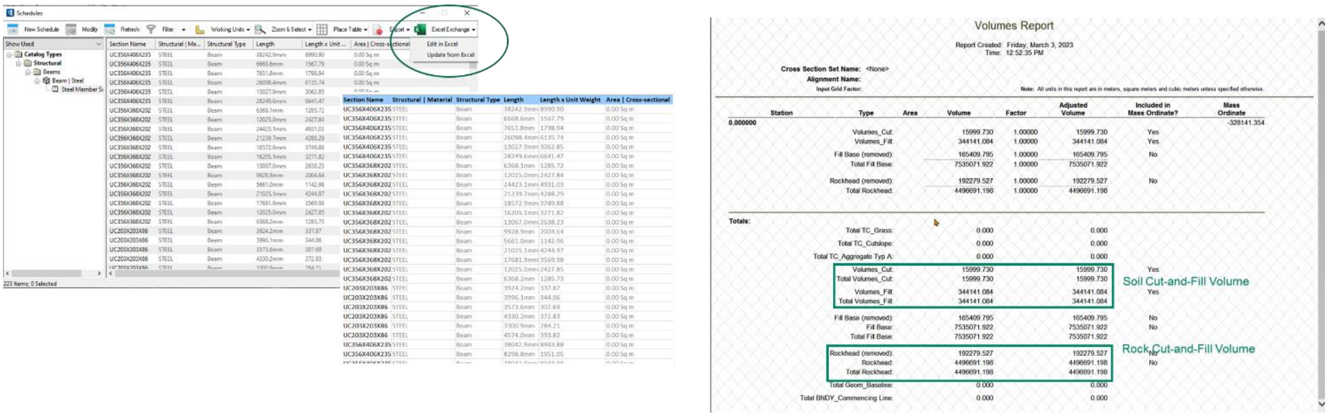

Figure 5: *Quantities of materials and volumes of earthworks for site formation design in OpenBuildings and OpenRoads*

3 Excavation And Lateral Support (Els) System Design

3.1 Conventional Design Approach

Similar to site formation designs, engineering geologists and geotechnical engineers appraise the ground conditions and site constraints and propose feasible schemes for the ELS systems with respect to the proposed/required final excavation profile. After considering the pros and cons of various schemes, high degree of collaboration between geotechnical engineers and structural engineers is often required in typical ELS system designs due to the iterative modelling of behaviour of soil-structure interactions to ensure the stability and serviceability of the ELS system.

Nevertheless, during construction stage where more information is revealed, the actual ground conditions, for instance the thickness of the soil stratum and/or the groundwater regime, may deviate from the expected ground conditions and site monitoring system, together with regular design review, are required to ensure stability of the ELS system.

3.2 Problem Statement

Commonly in ELS system design, the most difficult task is to fine-tune and optimise the ELS system without compromising the safety margin. Repetitive works are usually handled by the geotechnical engineers and structural engineers manually and the prolonged involvement of designers is rather time consuming and error-prone, especially for the changes (e.g., extent, layout, excavation level of the system) are required in the last minute.

While construction of the ELS system is always tied with that of permanent works, the tight construction programme of ELS system normally could not accommodate sufficient time for design review when the unforeseen conditions are encountered during construction stage. Subsequently, a more efficient workflow with the support from digital solutions which reduces the processing time for the iterative design and enhances accuracy and correctness of the ELS design is warranted.

3.3 Digital Solutions

The enhanced workflow represented in Figure 6 below make uses of digital solutions such as three-dimensional terrain models and ground models generated from LiDAR data and interpreted ground conditions (similar to Section 2.3.1 above), BIM approach and design automation with programming scripts (e.g., Microsoft Excel VBA, Python scripts) reduce the reliance of manual input as happened in conventional design approach. Apart from the enhancements similar to those discussed in Section 2, with the growth of geotechnical analysis software like Plaxis, design automation is enabled through Python scripts, which acts as a communicator between Plaxis and other conventional design tools in form of Microsoft Excel files.

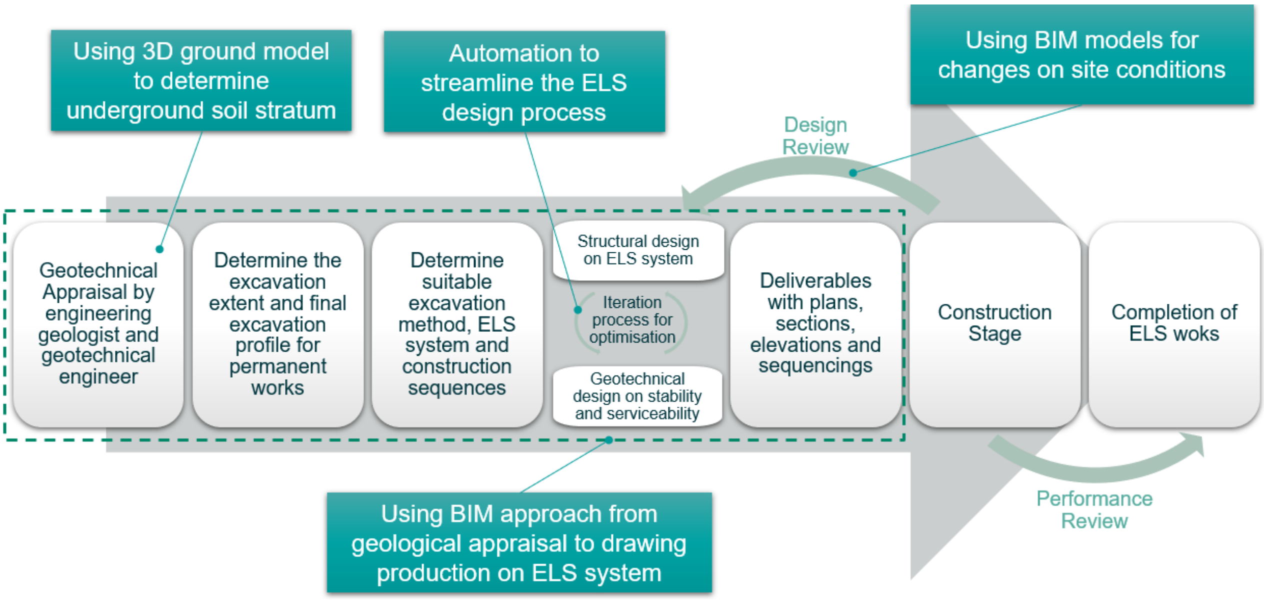

Figure 6: *Enhanced workflow using digital solutions.*

3.3.1 Generative Design

The ELS design process typically involves preliminary design of the layout of the pile wall system with or without shoring layout, depending on whether it is a cantilever wall system or a strutted wall system. It has long been a controversial issue whether a reasonable ELS layout could be generated from artificial intelligence (A.I.) to facilitate the design work. Whilst there is still not a reliable and robust A.I. system available due to unpredictability associated with the black box algorithm, an alternative generative design approach using programming technique has been explored.

Unlike working with A.I. where sufficient training based on preceding cases and verification is required, the experience and good practices of previous ELS system designs have been reviewed and consolidated into algorithm, which imitates how the designer "thinks" in reality and is coded with programming scripts in Microsoft Excel VBA. With the logic behind the algorithm, it takes the setting-out coordinates of the ELS system and maximum strut spacing as input and calculates the paired coordinates necessary to define the primary struts, secondary struts and corner struts of the system. The paired coordinates are then imported into other BIM software to generate the three-dimensional models of the ELS system. Figure 7 presents a shoring layout generated automatically from the algorithm programmed in Microsoft Excel VBA. The paired coordinate, together with the strut sizing, is then passed to BIM model using OpenBuildings Generative Component. Summary of strutting layout, including the size and length of each strut, could then be generated for design option comparison.

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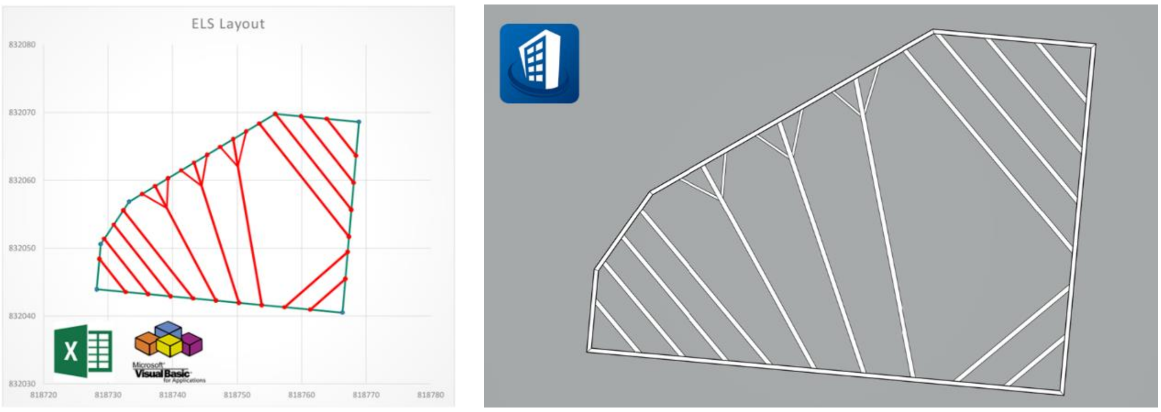


Figure 7: *ELS layout generated by algorithm using Microsoft Excel VBA and OpenBuildings Generative Component*

3.3.2 Automated Design

In order to minimise the need of manual input for the geotechnical analysis, which could be labour intensive and time consuming, Python scripts has been developed to connect the analysis with the design tools to streamline the conventional design approach with the use of standardised spreadsheet (see Figure 8).

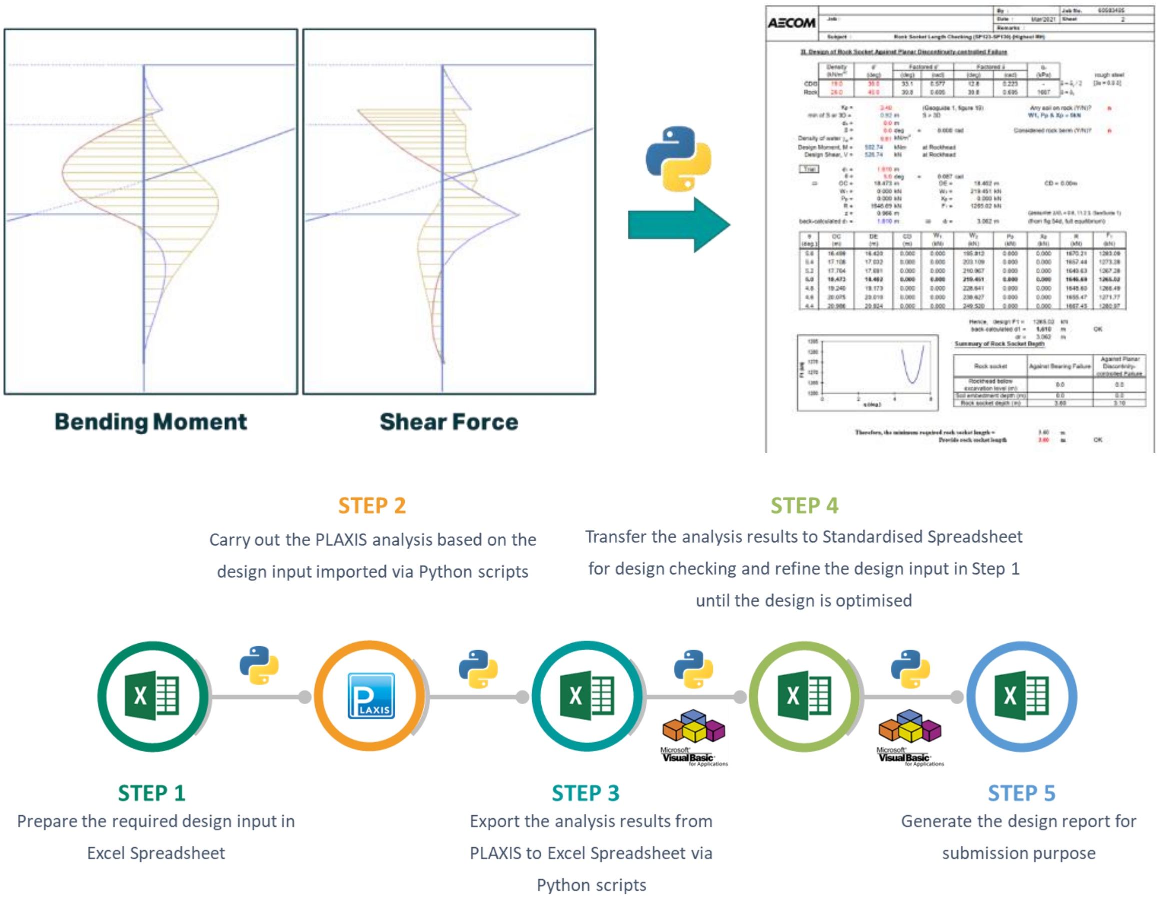


Figure 8: *Proposed data flow using programming scripts for ELS designs.*

Configuration, properties, modelling sequence and results are extracted from the geotechnical analysis software by Python scripts developed and summarised in table format which is readily connected with other standardised spreadsheets in Microsoft Excel. Should the capacity of the ELS system be exceeded, modification of input parameters could be done in Microsoft Excel and the information would be re-imported into the geotechnical analysis software by Python scripts directly, improving the consistency of the entire ELS system design.

Upon completion of the iterative design, the three-dimensional BIM model as shown in Figure 9 below could be regenerated/updated with the paired coordinate adopted in the revised design models such that it is always synchronised with each other.

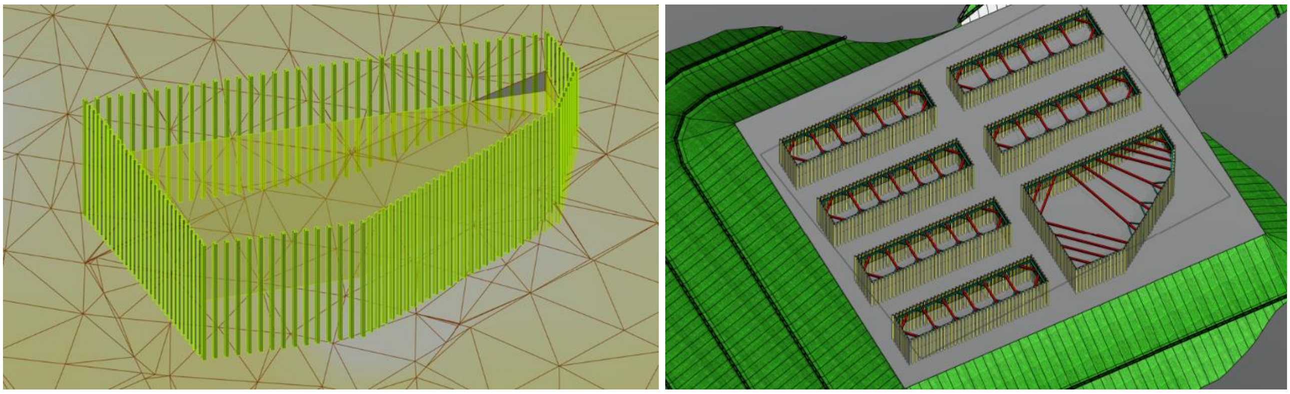
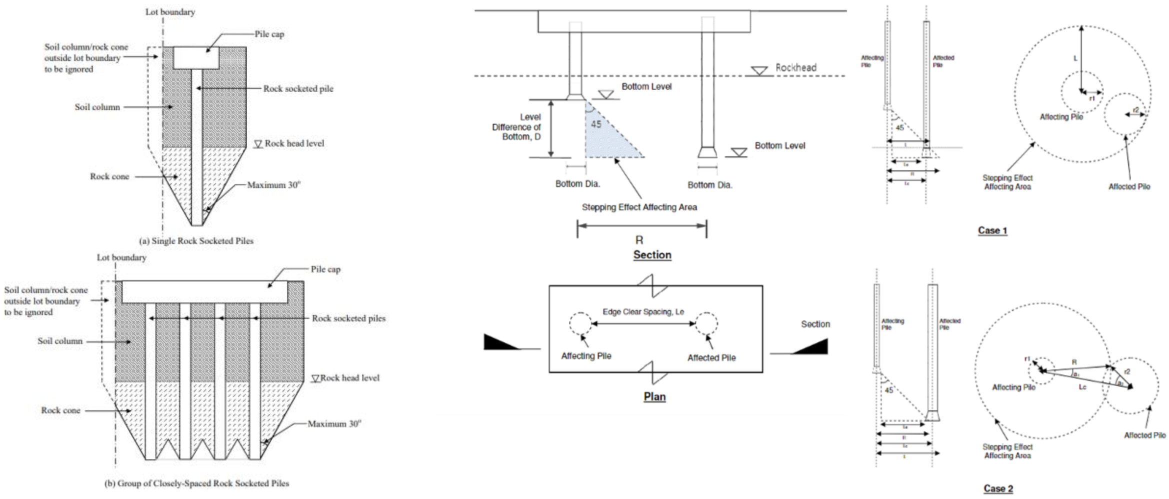


Figure 9: *3D BIM models to facilitate changes/reviews based on site conditions in OpenBuildings*

4 Foundations Design

4.1 Conventional Design Approach

In the conventional design approach, the sequential update of foundation designs from engineering geologists to geotechnical engineers and to draughtsmen may take up considerable time. This typically involves updating the interpreted rockhead contour generated from commercial software Surfer or other similar software with the information obtained from pre-drilling works, updating the interpreted rockhead level of the piles at the location of the piles and updating the design checking (e.g., structural capacity of the piles, bearing capacity of the piles, soil/rock cone stability, stepping effect due to interaction among piles) and drawings in accordance with the updated interpreted rockhead level.



(a) (b)

Figure 10: *(a) Design illustration of evaluation of soil/rock cone (extracted from CoP for Foundations, 2017 (BD 2017) (b) Design illustration of assessment of stepping effect*

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4.2 Problem Statement

Unless extensive ground investigation is carried out in the design stage, sufficiently fulfil the requirements for pre-drilling works of foundations, it is inevitable to carry out design verification based on pre-drilling works, of which the results come in batches usually. Based on the results of pre-drilling works, the interpreted rockhead contour and the associated foundation design is to be updated to reflect the latest known ground condition.

Once the interpreted rockhead contour is updated by the engineering geologists, the proposed termination depth might be increased or decreased and the design checking, especially those related to geometry in three-dimensional space, would need to be revisited to ensure validity of the foundation design. Very often this process is repeated frequently as the result comes back in a piecemeal manner, making it difficult to maintain the consistency between versions of foundation design and various documents (e.g., design calculations, design sections, elevations, and schedules, etc.). Apparently, this calls for a more efficient workflow with the support from digital solutions which reduces the processing time and enhances accuracy and quality of the foundation designs.

4.3 Digital Solutions

With a detailed review on the workflow on how we carry out foundation designs, we have considered the possibility of use of digital solutions to enhance the workflow and handle the repetitive tasks. It covers from the most straightforward use of three-dimensional representation of the interpreted rockhead, especially important in the location where complex geology is anticipated, the use of "virtual elements" for geometry related design checking, and the use of BIM software to produce construction drawings.

4.3.1 Evaluation of Soil/Rock Cone

As mentioned in Section 4.1, one of the most time-consuming tasks in foundation designs is to work out the spatial relationships among the piles (GEO, 2011). This is particularly difficult for closely-spaced piles as the combined effect of the pile group would generate a more complex geometry for the analysis (see Figure 10(a)). Although this could be simplified to two-dimensional planner problem, over-simplification may result in unnecessary long piles which reduce constructability on site. To properly address this, a new approach making use of the three-dimensional model with the introduction of "virtual element" as shown in Figure 11 is proposed to quickly obtain the volume of the soil and rock column directly from the model for further analysis.

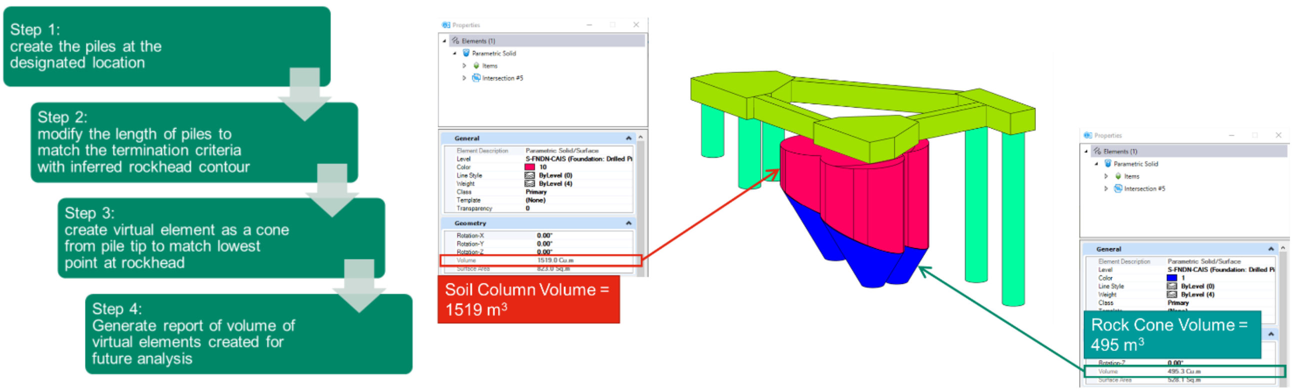

Figure 11: *Evaluation of soil/rock cone with the use of "virtual elements"*

4.3.2 Assessment of Stepping Effect

One should notice that the assessment of stepping effect involves the interactions among piles, which, in turn, require iterative checking in three-dimensional space and conventional checking in two-dimensional manner may take much longer time to determine the critical case, especially for closely-spaced piles. Every time when the foundation layout is revised, the assessment of stepping effect must be updated accordingly and the original critical case may have been shifted as a result of the changes.

Similar to soil/rock cone checking mentioned in the previous section, the use of "virtual elements" as shown in Figure 12 could be introduced to represent the load spread of piles and simple clash analysis could be adopted to check if the deeper piles would be subject to the lateral load induced by the shallower piles. This resolves the spatial relationship directly from the design model in three-dimensional space and thus enhances the efficiency of design checking.

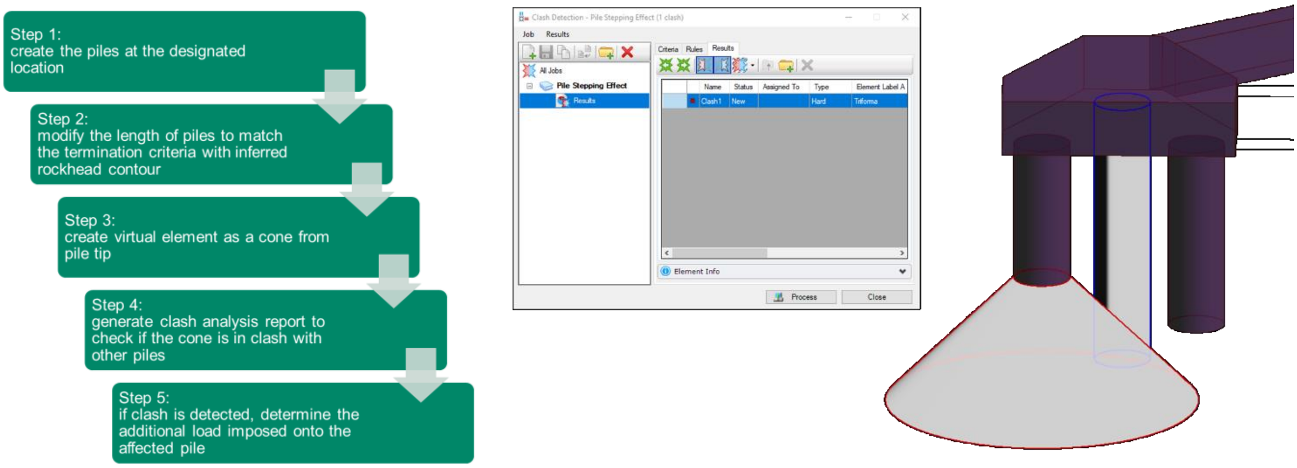

Figure 12: *Assessment of stepping effect with the use of "virtual elements"*

5 Discussions

Currently there is still no one-off software available in the market and, therefore, the use of a combination of software is still needed to complete the engineering designs and we will need to solve the issues associated with the compatibility of the software. While it is possible to develop a new one-off software to cater for the need of engineering designs, the time and cost for the development could be huge. A more practical way to deal with the compatibility of the software adopted is making use of an intermediate data file, which is commonly readable by various software (e.g., Microsoft Excel file), and programming scripts (e.g., VBA scripts, Python scripts) to connect the input and output among the software. This does not only resolve the compatibility issues among software that we adopted in the engineering designs, but also allows design automation, either completely or partially, which highly enhances the quality and efficiency of the design process. More importantly, it allows us to move on the journey of digital transformation from visualisation to design works.

The illustrative examples from Section 2 to Section 4 have shown that digital solutions developed so far enables compatible design of multiple systems, which, in turn, allows design review and optimisation to a higher level of a project. With this new digital solution, focus of compatibility of the systems is not only on clash analysis in spatial aspects but also the overall cost-effectiveness of the projects with better flow of information among the design analysis and evaluation tools.

Although the digital workflows discussed in this paper open the possibility to automate major geotechnical designs, making use of digital tools commonly available in the current market, this may not be exhaustive and is subject to change with future advancement in technology. With more support

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from industrial practitioners, it is expected that the advancement of digital solutions would be even more readily compared to the past few years and rapid development of new solutions is anticipated in the near future. More all-rounded digital solutions would be devised to accommodate a more comprehensive digital workflow, which could further enhance user-friendliness and efficiency of the design process.

Unavoidably, during the development of the digital solutions, it comes to our attention whether digital solutions, especially design automation done by the computers, could replace our engineers. Despite we have tried our best to accommodate the "good practices" in engineering designs in the digital solutions, it appears that engineering judgement and experience is still required to ensure the design generated by the digital solutions is a safe and robust design. In many of the cases, the digital solutions developed offer us some reasonable schemes supporting the feasibility of design automation; in some more complicated cases, it appears that the constructability, buildability, cost effectiveness and/or sustainability of the generated engineering solutions may not be fully optimised. Therefore, despite the digital solutions have significantly streamlined the conventional workflow, not until the digital solutions are proven to be robust enough to incorporate these factors in the engineering solutions, judgement from professionals is still essential.

Design optimisation is another major benefit that could be brought forward by digital solutions. Unlike the old days where only limited options could be developed due to limited resources and tight design programme, more design options with fine-tuning by parametric design could be carried out using digital solutions developed to allow qualitative option comparisons. Quantity of the proposed works could be taken from the design models readily with the programming scripts to fit into the bill of quantity for cost estimate. In future, there stands an opportunity to further connect the design models with tools to assess constructability, buildability and/or sustainability (e.g., BES(E) tools, BEAM+ assessment, etc.) to allow for a more holistic and comprehensive design option comparison (Penny *et al.*, 2021).

6 Concluding Remarks

With the advanced development of digital solutions, digitalisation in engineering has migrated to the next level in recent years. This paper discussed some efficient digital solutions developed for common geotechnical designs including site formation, ELS, and foundations and suggested how this could facilitate our design works, in particular for design optimisation, which aims to enhance cost-effectiveness, constructability and sustainability of the engineering solutions. Various conventional design approaches were reviewed in consideration of available digital tools for enhancement. Although there is still no one-stop solution that could carry out all design works in one suite, it is still possible to completely digitalise the workflow to reduce the processing time, especially for design optimisation using parameter design and for design changes due to site constraints and/or observations. Before a well-proven one-stop solution is available for the engineering design works, the feasibility of adapting "connectors" for data flow using programming scripting in common format (e.g., Microsoft Excel file) has been explored and it is proven to be successful in many cases. Not only can the "connectors" help to interrelate the input and output among software for design and visualisation purpose; it can also transfer relevant information from the design models directly to other design and/or evaluation tools for seamless design and design optimisation. Whilst design optimisation using digital solutions is made possible with the boosted-up of design efficiency, further study on enhancement of digital solutions with the potential of emerging digital technologies is always welcomed.

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