

A New Digital-based Approach to Automate and Optimize Geotechnical Design

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ABSTRACT

Geotechnical engineers always work with complicated terrains and geologies, which are usually interpreted from the topographical survey, LiDAR data, geophysical survey and ground investigation boreholes. In the old days, these data were mapped or modelled but could only be visualized or transformed to 2D sections for subsequent design, which may not be easily visualized in a 3D space. With the advancement of computing power and the development of digital tools, they enable engineers to work and visualize their design in a 3D environment. This paper will showcase the application of Rhinoceros 3D (Rhino) in various geotechnical designs. With the aid of Grasshopper, which is a visual programming language running within Rhino, some traditional spreadsheet-based designs can be automated in a new digital-based platform. This paper will discuss the workflow and algorithms of applying the Grasshopper visual program to assist in site formation and foundation designs supplemented by case examples, which include the determination of the pile rockhead level, the calculation of the rock and soil cone volumes, the visualization of the borehole stratigraphy, the automation of soil nail arrangement over complex terrain, the development of the excavation profile with multiple platforms and the full excavation and lateral support (ELS) system, etc. The application will also be extended to create model inputs for geotechnical analysis such as Oasys PDisp through COM Interface and PLAXIS through Jupyter Notebook.

Keywords: Digital, Workflow, Geotechnical Design

1 Introduction

We are living in a Digital Era benefited from the advancement of the computer power. The development of digital tools enables engineering industry being evolved to a new level of 3D visualization and design environmental. It improves the design capability to handle complex geotechnical problems in a holistic manner. It also enables design optimization and engineering analysis to be carried out in an efficient way.

Rhinoceros 3D (Rhino) is one of the 3D modeling programs available in the market. Rhino has been widely used in architectural and product designs. It can create, edit, analyze, document, render, animate, and translate curves, surfaces, solids, point clouds, and polygon meshes with no limits on complexity, degree, or size, which are particularly suitable for dealing with complex topographies and geological profiles of the geotechnical works. Grasshopper is a graphical algorithm editor included with Rhino. It is a visual programming tool, which requires no knowledge of programming or scripting, but still allows designers to develop algorithms to deal with geometries in various shapes. In this paper, the Author will showcase the applications of Rhino with Grasshopper in various geotechnical designs. The application will also be extended to create model inputs for geotechnical analysis. However, the adopted programs for geotechnical applications in this Paper are not unique and exhaustive.



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2 Design Workflow and Algorithm

2.1 Mapping Design Workflow

Mapping of the current design workflows can assist in identifying areas that could most benefit from the design automation. The workflow interface starts with data “Sources” from different disciplines or clients as inputs and the design product “Receivers” as outputs. These inputs and outputs are in the form of “Data Sets”, which are generally represented by drawing, spreadsheet, analytical model, etc. The workflow processes will consist of dataset being transformed or manipulated to a new dataset by means of a “Process”. Data sets shall be connected to processes and the processes shall generate new data sets, one after the other. The “Processes” generally consists of calculation, data extraction, decision making, etc. Figure 1 shows an example of design workflow for determination of the pile founding level.

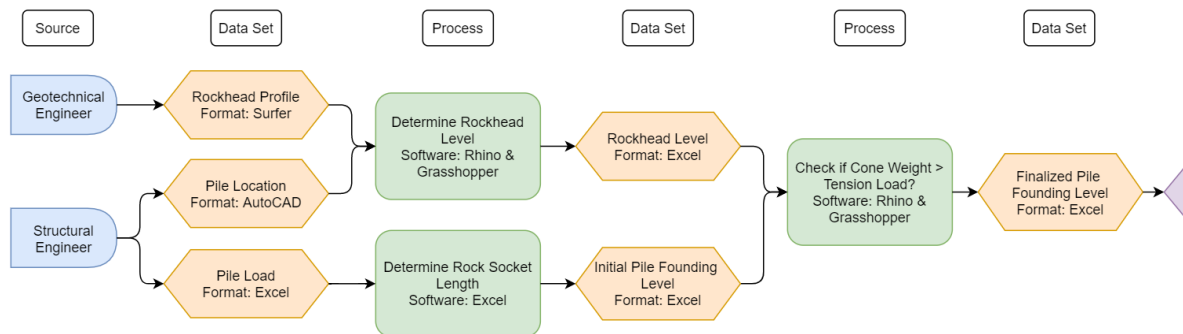


Figure 1: Example of design workflow for determination of rockhead level for rock socketed pile

2.2 Design Algorithm in Grasshopper

Once the design processes are identified, the adequate tools to automate the processes shall be selected. Following the example in Figure 1, the “Process” to determine the pile founding level can be automated by Grasshopper algorithm. First, define the circles representing the piles as a set of curves and the rockhead surface as a boundary representation (BREP) object. The rockhead surface can be generated from programmes such as Surfer as a set of points or Leapfrog as a mesh imported into Rhino and converted into BREP object or a patch surface. Second, project the circular curves onto the BREP surface. Third, find the lowest points of the projected circles onto the BREP using the bounding box function in Grasshopper. Finally, extract the z-coordinates of the lowest points, which represent the rockhead level of the piles. The algorithm is illustrated in Figure 2. Once the algorithm is set, it can generally be applied to other projects with no limit on number of piles.

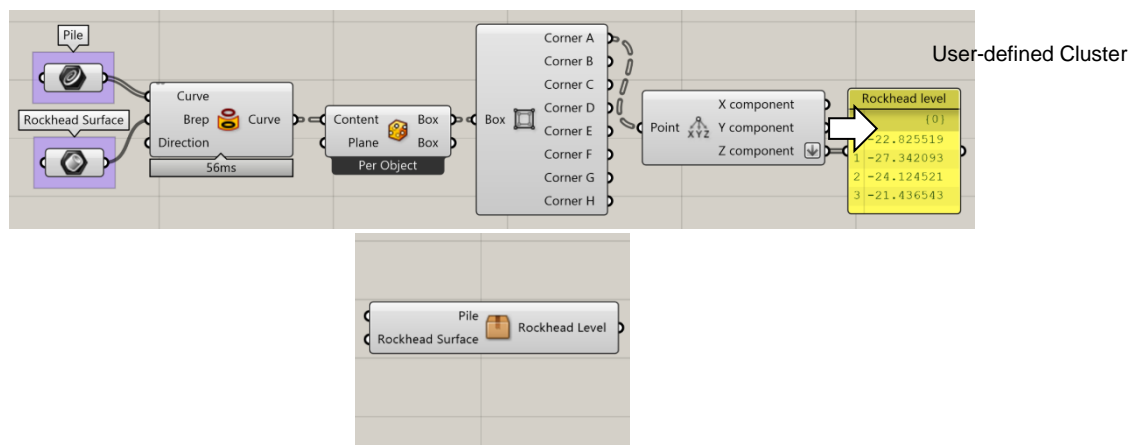


Figure 2: Algorithm in Grasshopper to determine rockhead level for 4 numbers of piles

Geotechnical design often involves complex geometries. The function categories of “Surface”, “Mesh” and “Intersect” in Grasshopper are highly applicable for geotechnical works. These enable the design engineer to create site topography, geological stratum, site formation and excavation profiles as surfaces or meshes in various shapes. It can evaluate the surface and mesh properties such as the area, centroid, dimension, relationships with nearby points, curvature, direction, etc. The “Intersect” function also enables splitting/trimming and the determination of union, difference and intersection of regions, meshes and BREPs. Clash analysis can also be performed on a set of shapes.

In routine foundation design, assessment of the effective weight of the tension cone, which comprises rock cone and soil columns, is required for piles subject to uplift forces according to the Code of Practice for Foundations 2017. However, precise calculation of the tension cone is difficult and time consuming as the boundary for tension cone calculation depends on the pile spacing and is limited by the lot boundary. The Voronoi function in Grasshopper can be applied in this situation. In mathematics, a Voronoi diagram is a partition of a plane into regions close to each of a given set of points. For each point, there is a corresponding region, called a Voronoi cell, consisting of all points of the plane closer to that point than to any other. The Voronoi diagram of a set of points is dual to its Delaunay triangulation. Figure 3 illustrates the algorithm in Grasshopper to determine the soil and rock cone volumes given the limiting boundary of the cone weight, the pile layout, the pile cut-off level, the rockhead level and the pile founding level. The angle of soil and rock cones can also be specified. Once defined, the rock cone for individual pile can be developed by offsetting the pile circle at the rockhead level. A ruled surface is then extruded from the pile base circle to the offset circle at the rockhead level, which is then capped at the top and bottom to form a solid rock cone. The same is performed for the soil cone. Using the Voronoi function and intercepted by the cone weight boundary, the Voronoi cells are then extruded over the same depth of the rock and soil cones and capped to form the solid cells for individual pile. Using the intersect function, the intersection as well as the volume between the solid cell and the solid cone can be determined for individual pile. The general view of the soil and rock cones in Rhino is illustrated in Figure 4. The algorithm in Grasshopper can be grouped and converted into a cluster, which can subsequently be created as a new category in Grasshopper for future use.

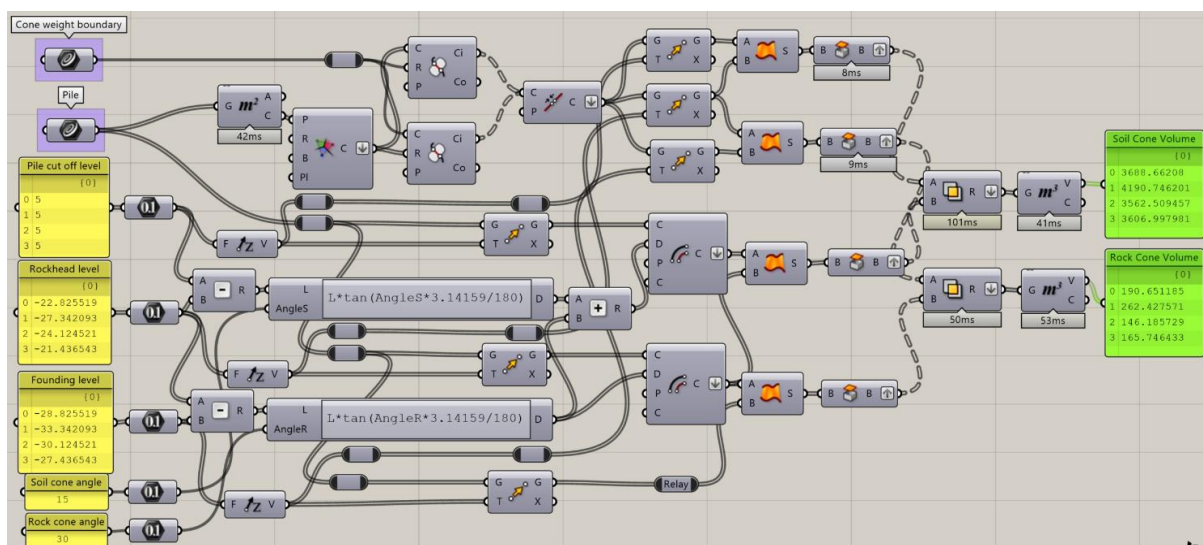


Figure 3: Algorithm in Grasshopper to determine soil and rock cones for 4 numbers of piles subject to uplift

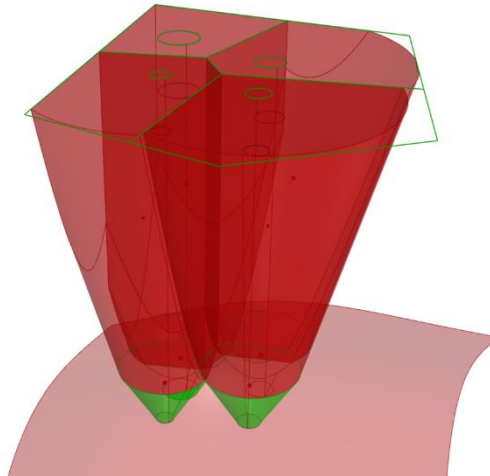


Figure 4: General view of soil and rock cones for a group of 4 numbers of piles bounded by a boundary in Rhino

3 Application of Automation in Geotechnical Design

3.1 Geological Profile

Proper ground model to represent the ground condition is essential for geotechnical design. There are some software programs in the market which can generate borehole sticks for visualization. However, the borehole information is usually limited to visualization and cannot be easily extracted to other platform for subsequent design application. Rhino and Grasshopper indeed provide a platform not only to visualize the borehole data in 3D space but also enable design engineers to integrate the geological model with the design models including the foundation, site formation and excavation and lateral support works created in Rhino. As such, the stratum information as well as the proposed geotechnical works can be reviewed holistically in a unified platform. The presentation style is also highly flexible and can be designed by the users to suit their design purpose. This concept of integrating the Ground Information Management (GIM) and the Building Information Management (BIM) models is also discussed in Mak et al (2021).

The author has imported the borehole data from Microsoft Excel spreadsheets in a designed format through Grasshopper to generate the borehole sticks in Rhino. The borehole sticks are mainly extruded from circles to represent each stratum based on the input levels for visualization. The modelling format is consistent with the Construction Industry Council (CIC) BIM Standard, which enables the integration with BIM model and BIM submission in the next stage. The individual strata from each borehole can be grouped to form a surface or solid to represent the generalized strata. This process can be automated in Grasshopper. The top and bottom points of the generalized strata can be sorted for individual borehole in Grasshopper. A mesh or BREP can then be generated based on these points to represent each stratum. Other information such as stratum labels, SPT N-values and total core recovery can also be imported. The borehole sticks as well as the imported information can be plotted in a geological section. An illustration of borehole sticks and the geological section are shown in Figures 5 & 6 respectively. When the data in Excel are updated, the borehole sticks and the geological sections will also be updated instantly. In addition, the geological profile can be uploaded to Rhino through Speckle, which is an open-source programme and can extract and exchange data in a real time manner between the most popular architectural, engineering and construction applications.

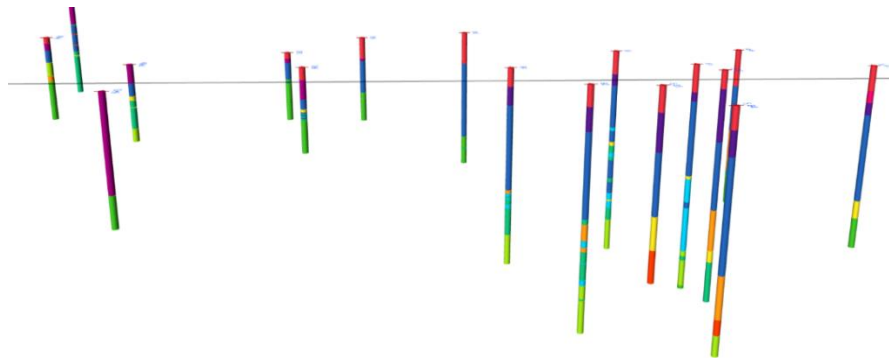


Figure 5: 3D View of borehole sticks generated by Rhino using Grasshopper algorithm

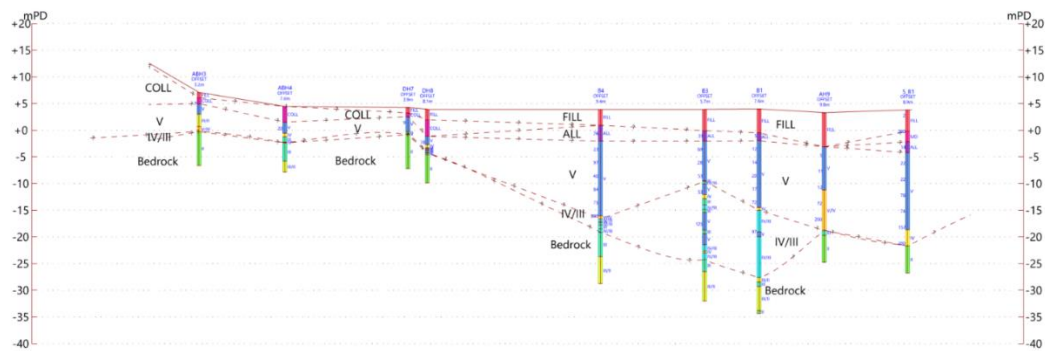


Figure 6: Typical geological section generated by Rhino using Grasshopper algorithm

3.2 Excavation and Lateral Support Works

Deep excavation over sloping terrain is challenging to geotechnical engineer. Sometimes, excavation involves hundreds of platforms at various levels, which makes the excavation profile highly complicated. The intersection with the existing topography will also enable the design engineer to decide if a perimeter pile wall is required or the formation level shall be adjusted to confine the excavation within the lot boundary. The “Intersect” function in Grasshopper enables multiple open cut excavation profiles to form a solid union, which is then trimmed by the existing topography in the form of BREP to obtain the excavation profile. Indeed, the formation of the open cut excavation profile is similar to the formation of the solid rock cone in previous example. Figure 7 illustrates an example of generating the excavation profile for more than a hundred platforms over a buildup terrain in a 3D space.



Figure 7: Automated open cut excavation profile for multiple platforms over existing slope

Deep excavation in bottom-up excavation sequence generally involves two main components: the pile wall and the steel shoring. Using the algorithm in Grasshopper, a series of point can be evenly distributed along a curve or polyline at given spacing to set out the centroid of the pile wall. The wall geometry can then be built and extruded to the existing ground and to the required toe level to achieve the required toe stability and to provide effective groundwater cut-off during excavation. For the shoring layout, the author has created a logic to automate the shoring arrangement. First, identify the corner areas with two lines of equal length where corner struts will be placed. Second, group the remaining curve or polylines into two groups such that the strut at one side of the group will support against the one at the other side of the other group. Third, based on the spacing of the main strut, corner struts and diagonal struts, determine the number of nodes for placement of struts and distribute them uniformly. Figure 8 illustrates an example of generating the preliminary shoring layout for a complex basement outline.

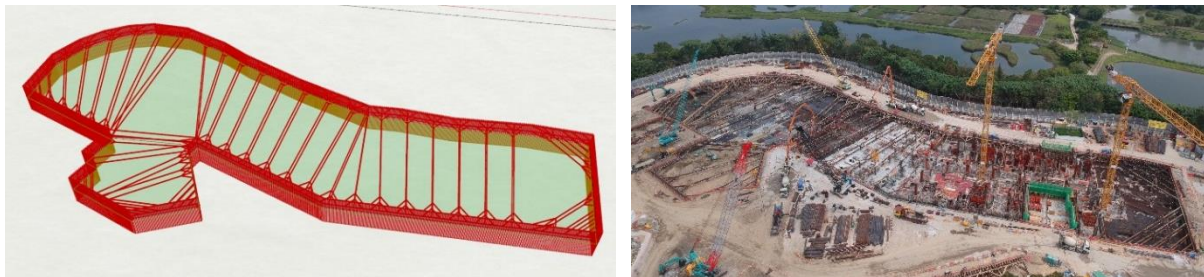


Figure 8: Automated shoring layout using Grasshopper algorithm

For uneven topography, the waling and the struts are not normally levelled. In such case, the strut members can be projected to the waling and create a space frame. This space frame contains the spatial information of the strut, such as the length, the inclination to horizontal, the planar angle normal to the waling, strut spacing, etc. Once the normal forces to the waling are determined from staged analysis, such as Oasys FREW or PLAXIS, the force for individual strut members can be readily determined for subsequent structural design using Grasshopper. With the lowest waling line being defined and the groundwater and geological profiles represented by BREPs in Rhino, cutting a section through the pile wall using the Grasshopper intersection function for BREPs and a plane will be able to retrieve the curves representing the groundwater table and geological stratum. These curves can then be converted into corresponding levels for toe stability check. The mathematical operation can indeed be carried out in Grasshopper such that the wall toe level can be optimized. Figure 9 illustrates an example of an ELS cofferdam with optimized wall toe levels.

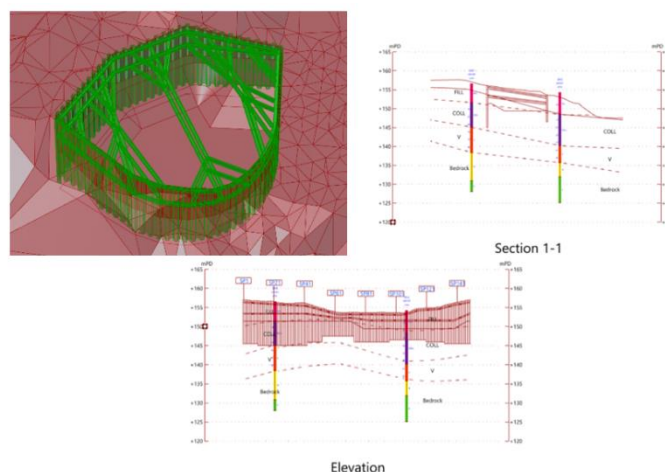


Figure 9: Example of ELS cofferdam over uneven terrain with optimized wall toe levels

3.3 Soil Nail Works

Soil nailing is an effective slope stabilization method widely adopted in Hong Kong. Typically, the spacing of soil nail varies from 1.5m to 2m both vertically and horizontally. A soil nail head is also required to enhance local stability. When placing soil nails over uneven terrain, it is difficult to be visualized in a 3D environment. Grasshopper has a category of vector function, which enables user to position the soil nail normal to the face of the terrain at a specified dip angle. First, define a series of horizontal surface planes and set the level of the planes as the vertical spacing of the soil nails. Second, intercept those horizontal surface planes with the existing topography represented by BREP (see Figure 10). Third, smoothen the intercepted curve to minimize sharp turning point of the uneven terrain. Forth, split the smoothened curve with nodes at equal horizontal spacing. Finally, position a line normal to the smoothened curve and dip at a specified angle to represent the soil nail. The length of the line is the length of the soil nail. Given the diameter of the soil nail, a circle can be extruded along the line to represent the physical dimension of the soil nail. Figure 11 illustrates the automated soil nail arrangement over an uneven terrain in 3D space. In Grasshopper, there is a function to carry out clash checking. This function enables user to identify the clashed soil nails so that their orientation and dip angle can be further refined.

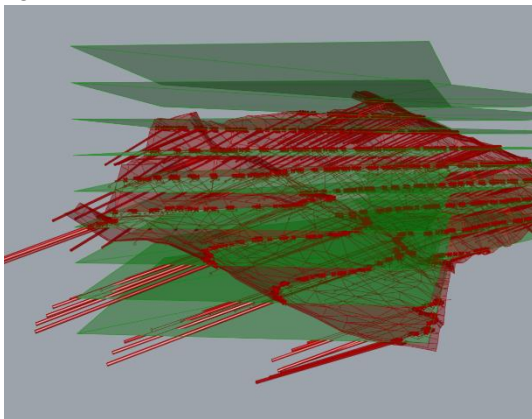


Figure 10: Intersect of the horizontal planes and the existing topography

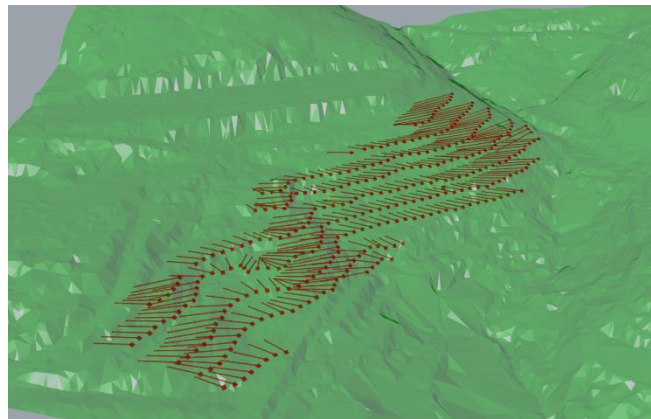


Figure 11: Automated soil nail arrangement on existing topography

4 Automation in Computer Analysis

The Rhino model contains all the geological, groundwater as well as the topographical information. These profiles can be easily manipulated through Grasshopper to extract the desired input data in a designated format for computer analysis. The data can first be extracted to an Excel spreadsheet to facilitate the inputs. One of the applications is to provide input data for Oasys PDisp by converting various geological profile to discrete sets of stratum levels under a given grid pattern. This process is particularly useful for simplifying the complicated geological profile to a generalized flat plane as inputs in PDisp. In PDisp, the analysis area needs to be divided into soil zones in a grid pattern. Each soil zone shall specify a soil profile with soil stratum levels. Traditionally, the stratum levels need to be read off manually from the inferred contours for different soil layers in every grid. While the geological profile is usually non-uniform, it is tedious and time-consuming to produce a high-resolution geology in PDisp.

With the aid of Grasshopper, the geological profiles represented by BREP in Rhino at each soil zone can be intersected by the cells of the grid pattern and the centroids of the intersected profiles can be obtained. The cell coordinates, which represents the soil zones, and the levels of the centroids, which represents the levels of the soil profiles, can then be extracted to an Excel spreadsheet. Figures 12 illustrates the cells of the grid pattern projected onto the geological profile.

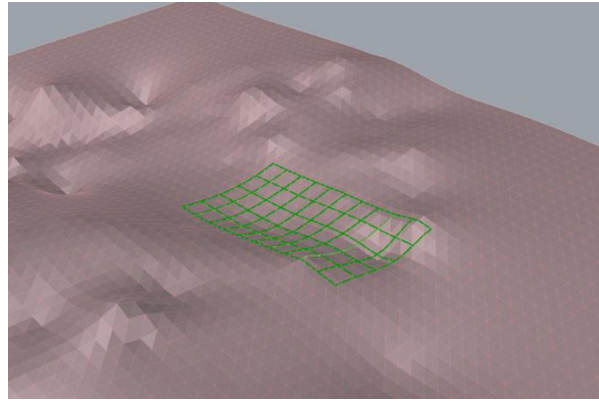


Figure 12: Projection of grid on geological profile in Rhino model

In order to import the data objects into PDisp, this can be achieved via the Component Object Model (COM) Interface. This enables external programs to pass information and instructions to and from PDisp, including the Visual Basic for Applications (VBA) in Excel. As such, the design process can be streamlined and automated from data input from Rhino through COM Interface in Excel to PDisp. Using this process, the time saving is substantial, and the model can be effectively refined by reducing the size of the grid to achieve a more accurate and prompt estimate. Figures 13 and 14 demonstrate the soil zone and soil profile in PDisp model automatically generated using the COM Interface. The COM Interface is also available in other geotechnical software under Oasys and similar design process can be established.

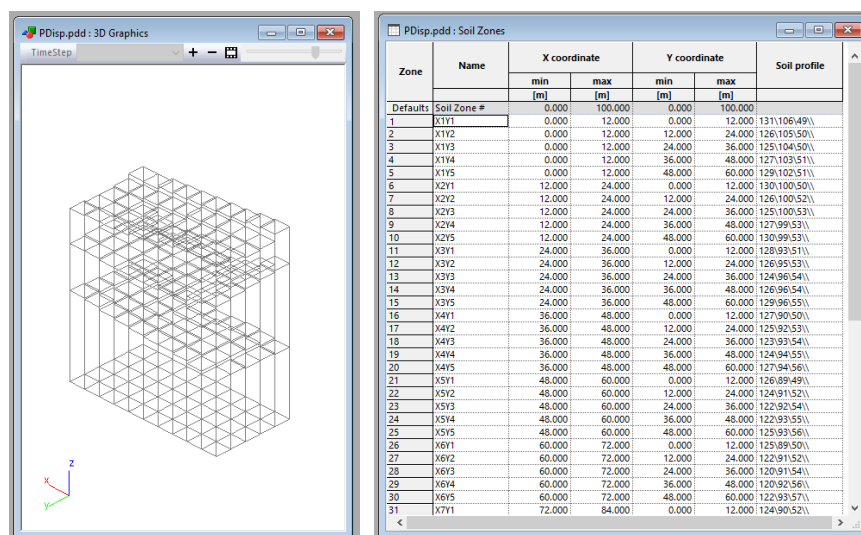


Figure 13: Soil zones with soil profile in PDisp using COM Interface

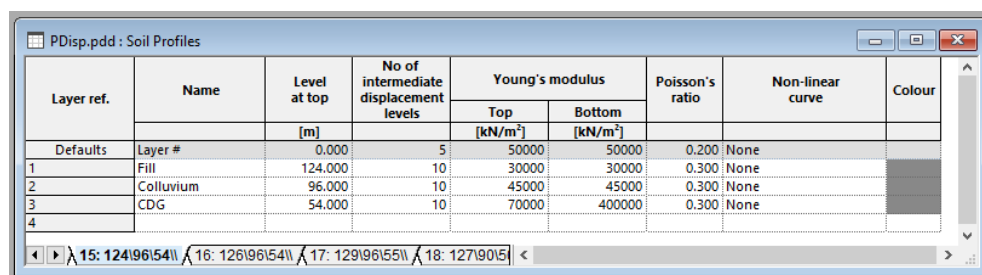


Figure 14: Soil profile with assigned geotechnical parameters

In addition to Oasys, remote scripting enables PLAXIS analysis to be run through Jupyter Notebook. It is a web-based open-source interactive computing platform. It can control PLAXIS in a remote

manner through the python scripting. The geometries in Rhino are first converted into polygons, polylines and lines, which are then exported to a pre-defined format in Excel with all the input parameters required in PLAXIS. These parameters include the soil polygons representing the geological stratum and the excavation profile, the lines representing the wall plate and node-to-node elements, and the polyline representing the groundwater profile. The python script in Jupyter Notebook can then read the Excel data and run PLAXIS commands to drive the staged inputs and analysis in PLAXIS. Figure 15 illustrates the use of Jupyter Notebook to connect with PLAXIS and automate staged excavation input in PLAXIS.

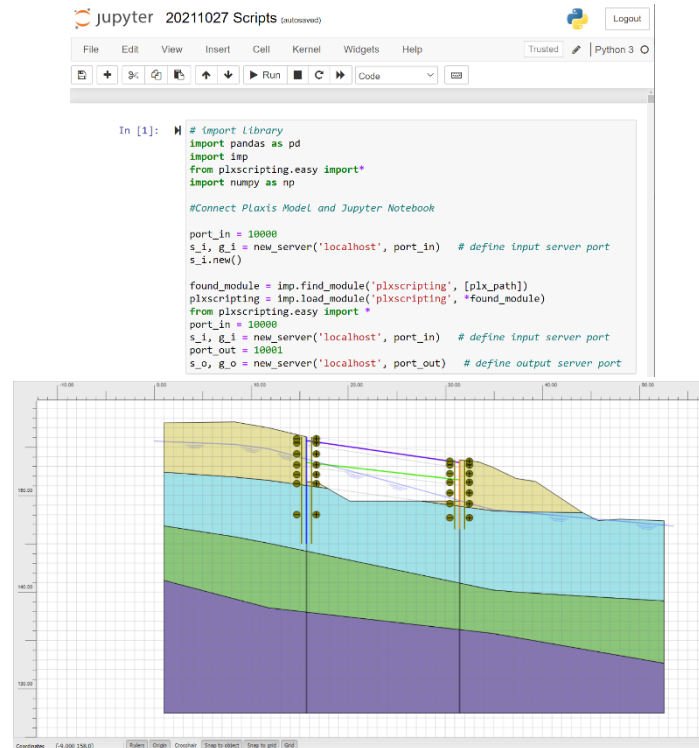


Figure 15: Example of using Jupyter Notebook to automate staged excavation input in PLAXIS

5 Design Efficiency

Traditionally, the BIM model is generated after the design is nearly finalized or frozen. With the capability of visual programming and the pre-defined algorithms as presented in this paper, a preliminary 3D model can be built within couple hours or a day depending on the project scale at the beginning of the design stage to integrate the ground model, geological profile as well as the intended geotechnical design into a single 3D platform. Once the integrated 3D model is built, it enables the geotechnical engineers to extract useful design data such as rockhead level, shoring and soil nail arrangements as illustrated in previous examples for subsequent design and to facilitate prompt quantity estimation. The algorithms also enable the generation of input data for geotechnical analysis such as toe stability check, settlement check, slope stability analysis, finite element modelling, etc. The greater benefit is that once the 3D model and the design workflow and algorithms are set, any changes in geological condition due to additional ground investigation boreholes or any update of geotechnical design in the 3D model can provide instant update to all the input data for repeated geotechnical analysis. Based on the experience of the author, it is believed that the time saving by using the pre-defined algorithms on routine engineering design is enormous and could possibly be in the order of 25% to 50% for beginners to greater than 75% for experienced users.

6 Benefits of Automation

The benefits gained on design automation not only enable faster delivery of the design, but also enable better and optimized design to be produced. The visualization of the integrated geological and design models in 3D space enables the design engineer to have a better understanding of the site and the geological constraints. During the design development, these constraints can be considered holistically such that the ground risk can be addressed at early design stage. The integrated model also facilitates better communication with the clients and coordination among the engineering team and the BIM coordinator. The integrated model in Rhino enables computer inputs to be generated for analysis in a more efficient and accurate manner. Any changes in Rhino can also be automatically updated following the same workflow and algorithm in Grasshopper to re-create the model as well as the data inputs for computer analysis. The enhanced digital capability also enables more design sections to be created for analysis and optioneering to drive data-driven decisions. Ultimately, it can provide optimal design outcomes and high-quality outputs for clients in lesser time.

7 Conclusion

The development of digital tools enables design engineer to visualize, automate and optimize their design under a digital-based platform. Mapping of the design workflows and identifying the time-consuming processes can maximize the effectiveness of the design automation. The Author has showcased the applications of using Rhino with Grasshopper to automate various geotechnical designs, including pile foundation, excavation and lateral support and soil nailing works, create model inputs for computer analysis and perform design calculation and stability check. Grasshopper is easy to learn and use. It requires minimum knowledge of programming or coding. There are plenty Grasshopper plug-ins available for downloading. Besides, the designers can create their own clusters and categories in Grasshopper and they are transferable and applicable to multiple projects. These clusters can always be replaced individually if a better one is created or developed without affecting the entire algorithm. The future development of design automation is to link the results of the computer analysis back to update the design model in Rhino. The finalized design model shall then be transformed to 3D BIM model for design submission and drawing production.

8 Publisher's Note

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