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Automatic Finite Element Modelling and Parameter Determination for Geotechnical Design

Ronald B.J. Brinkgreve, Sandro Brasile

Abstract: This article describes how efficiency in geotechnical engineering involving finite element (FE) modelling can be improved by automation. An important part of geotechnical FE modelling involves the creation of an underground model and the determination of soil and model parameters. It is explained how Automated Parameter Determination (APD) based on CPT data can be used in conjunction with geological modelling to create the necessary input for a FE model. An example demonstrates the entire workflow. The system is transparent and extendable. It supports the geotechnical engineer in the complex task of parameter determination, while retaining the responsibility at the user. Automation can help reducing the spread in results when different geotechnical engineers analyze the same problem, and hence, it can contribute to the confidence in the use of advanced numerical methods for geotechnical design.

1 Introduction

Our continuous drive for professional advancement and efficiency has led to the development of numerous software products enabling geotechnical engineers to solve geotechnical problems in shorter time. In the early days of personal computers, pioneers developed codes to implement simple solutions based on classical methods for bearing capacity and stability. In the same period, non-linear numerical methods on mainframe computers (such as non-linear spring models, limit equilibrium (LE) models, finite difference (FD) models and finite element (FE) models) were turned into more user-friendly desktop applications. The evolution of these methods over time, from 2D to 3D to 4D, in conjunction with advanced constitutive models, has been a gamechanger for geotechnical analysis, both in research and practice. However, some people argue whether this has resulted in more reliable geotechnical designs. Surely, the current numerical tools inherently provide much more insight in non-linear deformation behaviour, soil-structure interaction, and complex mechanisms, but the accuracy of results highly depends on the user's ability to determine the right input parameters.

Besides the development of advanced analysis tools, much progress has been made in automation of data collection, storage, processing, and visualization. With the right software tools, the generation of a geotechnical site investigation report has become a matter of only a few mouse-clicks. However, the quality of sampling and testing is still left to the experience of the field worker or lab technician. Likewise, the interpretation of data and the translation into soil and model parameters highly depends on the experience of the geotechnical engineer. On the one hand this is good, because it emphasizes the role and expertise of a geotechnical engineer in a multidisciplinary construction or infrastructure project. On the other hand, it may lead to (significant) differences in results when different engineers provide a solution for a well-defined problem based on the same set of data. This is because the interpretation of data is not straight-forward or 'by the book', so it depends on the experience of the engineer and the methods that he or she adopts. Benchmark studies, such as those organized and reported by Prof. Helmut Schweiger, exemplify this situation (Figure 1).

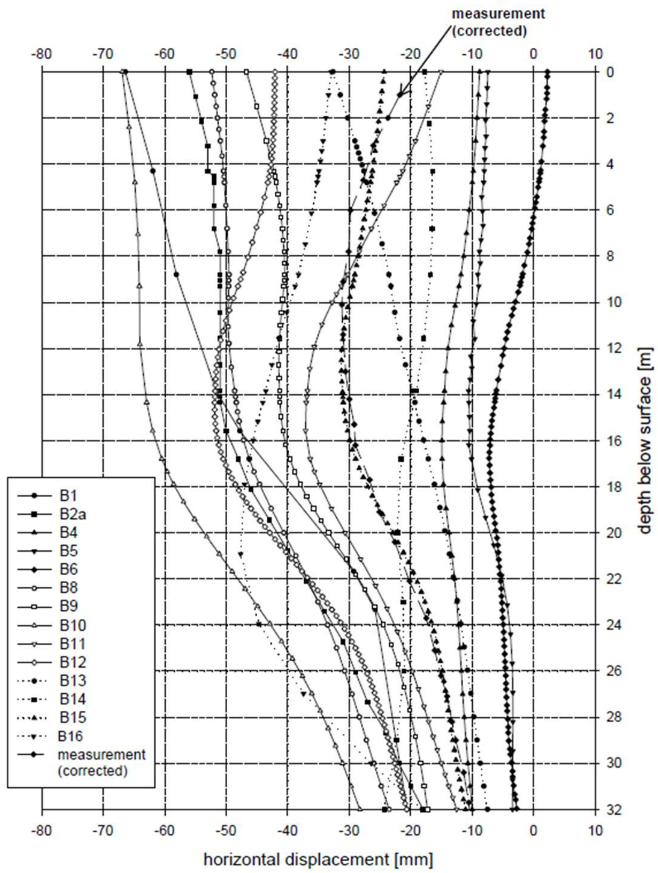

Figure 1: Calculated wall deflection for a well-defined multi-stage excavation problem. Different predictions, all based on the same set of input data, give a large bandwidth of results (after Schweiger, 2002)

A more recent trend in construction related software applications includes Building Information Modelling (BIM), which has meanwhile evolved towards Digital Twins. In fact, BIM and Digital Twins bring different categories of software developments (data collection, storage, processing, visualization, modelling, analysis, design) from different disciplines together and connect this for the benefit of a construction project as a whole and all its stakeholders. Where BIM focuses on the design and construction process, Digital Twins include the entire project lifecycle, including maintenance, retrofit, and decommissioning at the end of its lifetime. It aims to provide an up-to-date digital copy of all relevant aspects of a real-world project with all details at all times.

The advantages of BIM and Digital Twins are multiple; three are highlighted here:

- It integrates the involvement and facilitates collaboration of different disciplines and stakeholders in a project.

- It allows for protecting and sharing project-related information in an online environment.
- It allows for cross links between data, models and analysis results: if a model (or the situation in reality) is updated, the corresponding analyses, results and design consequences can be updated easily.

The development of Digital Twins is facilitated by the interoperability that is built in modern software applications. It is based upon a well-defined Application Programming Interface (API) to link different software applications together, as well as templates or schemas for data exchange. The Python programming language seems ideal for making connections between different applications and to provide technical solutions. There are numerous Python libraries online available for free to perform mathematical operations, process data, visualize results, etcetera, and their number is increasing every day. Universities facilitate students and research staff to acquire Python programming skills to solve (technical) challenges. This trend is also picked up by engineering companies, allowing (young) engineers to build new applications around established commercial software packages, thereby attempting to create a competitive advantage.

Despite all automation, the interpretation of data and the translation towards soil and model parameters for geotechnical analysis and design is still a 'human task' in the geotechnical workflow. Some engineers believe that this situation must remain to leave this responsibility with the geotechnical engineer. The authors of this article believe that automation may help to facilitate the geotechnical engineer in doing his/her job more efficiently while retaining their responsibility. Moreover, it may reduce errors due to human misinterpretation or transfer of data. Finally, it may help to narrow the bandwidth of results when different engineers solve the same problem, and hence, it may improve the confidence in numerical analysis.

Section 2 of this article describes how geotechnical finite element modelling can be automated and integrated in a Digital Twin environment. Section 3 describes the process of automated parameter determination based on correlations from field test data. Section 4 demonstrates an example. The conclusions are written in Section 5. The References section ends this article.

2 Geotechnical finite element modelling in a Ditigal Twin

Since the early development of dedicated geotechnical finite element software as a desktop application, the software packages include all facilities to:

1. Build the model geometry consisting of a stratigraphy (soil layers), structures in/on the ground and the intersection / aggregation of both.
2. Apply boundary conditions, loads and hydraulic conditions
3. Provide soil and structural properties
4. Define calculation phases representing various stages of construction
5. Define and generate a finite element mesh
6. Run the calculations
7. View the results

A Digital Twin of a real-world project including all relevant data can provide input to build a finite element model, but the data must first be filtered and transformed. For example:

1. Digital terrain models in combination with borehole data can be used to create a three-dimensional underground model. To create a model that is suitable to generate a consistent finite element mesh requires thin soil layers to be filtered out from individual boreholes (while maintaining their influence in the model, if they are relevant) or combined into layers with a finite (minimum) thickness. Consistent layer boundaries and volumes shall be formed by connecting corresponding layers from the various boreholes. Challenges in this process are:
    a. A digital terrain model has a higher density and may be inconsistent with the borehole data.
    b. A straight-forward connection of corresponding layers across boreholes may lead to intersecting (inconsistent) layers in the likely case of a non-horizontal ground surface and/or layering.
    c. The order, number and type of soil layers in the various boreholes may differ from one to another.

    As a result, this process generally requires human interaction, although there is progress in applying Artificial Intelligence (Machine Learning) for automatic layer determination (Rauter & Tschuchnigg, 2022).
2. Once a consistent underground model has been created, a structural model may be added to the system. This gives other challenges:
    a. Structural models, especially based on technical drawings, may suffer from small inaccuracies that may lead to small gaps or badly shaped elements when processed in a finite element environment (i.e. mesh generation).
    b. Real-world structures having a particular shape (profile) and volume need to be translated into an equivalent mechanical model. They may be represented by beams (line elements) or shells (surface elements) with equivalent geometrical and mechanical properties but with no volume.
    c. Intersecting underground model and structural model may lead to thin gaps or overlaps which may lead to badly shaped elements or other inconsistencies upon mesh generation. Therefore, some geometric parts may need to be adapted, depending on accuracy and priorities of the model components.

Rather than combining an underground model and structural model in a finite element environment, there is a need for an intermediate ‘conceptual model’ as part of a Digital Twin, which is a consistent equivalent model that contains all interpreted, translated, intersected, and aggregated data for any type of analysis. From a conceptual model a further choice can be made as to which type of analysis shall be performed. This could be based on Limit Equilibrium (LE) models, Finite Difference (FD) models or Finite Element (FE) models, either 2D (cross section) or 3D, depending on the accuracy and complexity requirements for individual situations. The input data for the selected type of analysis shall be derived from the conceptual model rather than from the original data directly.

Although tools exist to overcome some of the aforementioned challenges, the generation of a geotechnical finite element model in a Digital Twin environment still needs quite some human interaction. It requires more research and development before this process can be fully automated. Nonetheless, the current capabilities are already a significant step forward in terms of efficiency and error reduction compared to the situation before the introduction of Digital Twins.

3 Cone Penetration Testing

One of the main challenges in geotechnical engineering is to determine representative soil and model parameters. Especially in an early stage of a project, limited soil data are available. At project locations that are well accessible and involve relatively soft ground conditions, cone penetration testing (CPT) can be a cheap and useful way to explore the underground. Over the years, CPT has gained much popularity in site investigation. The equipment has strongly evolved; the latest system provides a fully automated continuous operation (Storteboom et al., 2022), and the processing of results and transfer of data in a standard format (GEF, AGS, DIGGS, etc.) can also be done automatically.

Several companies have compiled their own proprietary database with CPT data. In The Netherlands, a large public database exists of freely accessible CPT data (and other subsoil data), mostly from infrastructural projects: Dinoloket (www.dinoloket.nl/en). This database, together with Table 2b of the Dutch geotechnical design code NEN 9997-1 (2016) and ground surface elevation data from AHN (Actueel Hoogtebestand Nederland; www.ahn.nl), are valuable sources of information for a desk study by students and professionals exploring the geotechnical challenges for a project in The Netherlands.

The interpretation of CPT data (i.c. cone resistance q_c, shaft friction f_s, friction ratio R_f and pore pressure u_2, measured every 1 or 2 cm in depth) is internationally based on Robertson's method (Robertson 2009, 2010, 2016) in which individual CPT readings are translated into Soil Behaviour Type (SBT). The SBT, as the name says, tells something about the type of soil *behaviour*; not necessarily the type of soil, although it is often interpreted like this. Next, subsequent SBTs in depth with similar q_c- and f_s-values are combined into soil layers (stratification). For each layer, average q_c-, f_s- (and u_2-) values are calculated and used to determine soil properties and parameters.

Where the translation of CPT data to SBT is fully automated (various software packages exist that do this and give similar results), the determination of soil layers, soil properties and soil parameters is often a 'manual' task of a geotechnical engineer. The outcome of this process depends on the 'choices' that the engineer makes. Some of these choices are:

1. Which version of Robertson's method to use: based on normalized (2009) or non-normalized (2010) CPT parameters?
2. Where to put the boundary between one soil layer and the next? Combining different thin layers into thicker layers?
3. Which method(s) or correlation(s) to use to obtain representative parameter values?

It is clear to see that a different layering in point 2 will lead to different averages per layer and hence, different parameter values. More prominently, point 3 results in different parameter values since different engineers favour different methods or correlations, and their limitations are not always clear or considered.

Ideally, the use of field test data, such as from CPT, shall be completed with lab testing data to enable more accurate parameter determination. However, especially in an early stage of a project, good quality lab testing data are often not available. If such data *are* available, it shall be realised that the lab tests may not cover the most prominent stress levels, stress paths, strain levels and strain rates that are representative of what the soil encounters during the construction process or the lifetime of the project. Therefore, parameters determined from lab tests may not be fully representative of the soil behaviour in the practical application. The same can be said about CPT and the use of correlations, but CPT data can still be a good starting point in absence of more reliable soil data.

4 Automated Parameter Determination

To reduce the variation in results of numerical analysis due to variations in parameter determination, a system for automated parameter determination (APD) has been proposed by the first author and co-workers (Brinkgreve 2019; Van Berkom 2020; Van Berkom et al. 2022; Marzouk et al. 2022). APD determines 'paths of correlations' using a so-called Graph method (Van Berkom 2020), starting from CPT parameters via intermediate parameters (such as relative density, plasticity index and soil state parameters) to final soil and model parameters. APD includes more than 80 parameters and more than 170 correlations, including information about their applicability, limitations, and backgrounds. Several correlations on soil properties were taken from Kulhawy & Mayne (1990) and publications from Prof. Peter Robertson's CPT website (https://www.cpt-robertson.com/publications/) as well as correlations to derive the parameters of the Hardening Soil small-strain constitutive model (Benz 2007), including those from Brinkgreve et al. (2010).

The APD system is transparent in the sense that outcomes can be traced and verified; it is extendable in the sense that additional parameters and correlations can simply be added without the need of programming, as they are stored in comma separated value (CSV) files; and last but not least, the standard set of parameters and correlations has been validated by a team of researchers from academia and industry. For the latter, the free accessibility of CPT data in Dinoloket has been very useful.

The APD workflow is as follows (based on a single CPT):
1. Selection and reading of a CPT
2. Translation of individual CPT readings to SBT
3. Stratification procedure to form soil layers based on a minimum layer thickness and averaging of CPT data per layer
4. For each layer: parameter determination based on the Graph method
5. Export of layering ('borehole') and parameter sets

The APD workflow can be integrated in geotechnical finite element software, or it can be part of the creation of an underground model within a conceptual model in a Digital Twin environment (Chapter 2) from which a numerical model is extracted.

APD can be used repetitively to create multiple 'boreholes' from which a 3D underground model is created. In many cases, the ground surface and soil layers are non-horizontal. The ground surface can be taken from elevation data as 2D cross sections or 3D digital terrain models (point clouds, grids or triangulated surfaces), provided that the resolution is sufficiently accurate. As stated before, the creation of layer boundaries from multiple boreholes still requires some manual interaction, but the entire workflow can be automated to a large extent.

After consistent layer volumes have been created, parameter sets may be assigned based on a representative CPT. Alternatively, they may be recalculated per layer using point 4 of the APD workflow, based on 'averaged' CPT data from multiple CPTs.

5 Example

To demonstrate the automated finite element modelling and parameter determination process as described in the preceding chapters, an example is elaborated here. The example involves a location near the Zalmhaven tower in Rotterdam (Figure 1). This building was completed in 2022, and with its height of 215 m it is the highest residential building in The Netherlands.

Figure 1: Zalmhaven tower, Rotterdam (after Schippers et al., 2021)

To build the underground model for this example, existing CPT data was obtained from Dinoloket. A total of 18 CPTs were subsequently interpreted using APD and exported as combined boreholes in a format that can be read by Leapfrog Works (Seequent 2022), a geological software package that is mostly used for mining applications. Leapfrog allows for visualization and processing of underground data. The boreholes were turned into a 3D underground model with consistent layer volumes. The boundaries separating the layer volumes were exported to the PLAXIS 3D finite element software. The parameter sets of the respective layers were obtained from a representative CPT for which APD automatically determined the parameters of the Hardening Soil small-strain stiffness model (HSsmall) based on APD's standard set of correlations.

The model could have been further elaborated to include structures and loads, to define calculation phases and to perform all other steps of finite element modelling, but these steps were not performed and are therefore not presented here.

5.1 Selection and interpretation of CPTs

The following 18 CPTs in Geotechnical Exchange Format (GEF) were obtained from Dinoloket (Table 1):

Table 1: CPTs used for the creation of the underground model (Source: Dinoloket.nl)

CPT000000081615_IMBRO_A.gef	CPT000000081626_IMBRO_A.gef	CPT000000150505_IMBRO_A.gef
CPT000000081619_IMBRO_A.gef	CPT000000081627_IMBRO_A.gef	CPT000000150791_IMBRO_A.gef
CPT000000081620_IMBRO_A.gef	CPT000000149509_IMBRO_A.gef	CPT000000150810_IMBRO_A.gef
CPT000000081621_IMBRO_A.gef	CPT000000150310_IMBRO_A.gef	CPT000000150913_IMBRO_A.gef
CPT000000081623_IMBRO_A.gef	CPT000000150325_IMBRO_A.gef	CPT000000150975_IMBRO_A.gef
CPT000000081624_IMBRO_A.gef	CPT000000150488_IMBRO_A.gef	CPT000000150991_IMBRO_A.gef

All 18 CPTs were automatically processed by APD using the following settings:

- Interpretation method: Robertson 2010
- Minimum layer thickness: 1.0 m
- Assumed groundwater level: 1.0 m below ground surface

Figure 2 shows an example of an interpreted CPT based on CPT000000081624, which is considered representative for the underground to a depth of 35 m. The soil profile is typical for Rotterdam, consisting of a sandfill layer on top, underlain by Holocene deposits with mostly soft sandy clay (and peat) to a depth of around 15 m, under which the Pleistocene layers are found with mostly medium dense sand and some intermediate clay layers.

It should be noted that for the actual design of the Zalmhaven tower new proprietary CPTs were taken to a depth of 85 m (Schippers et al., 2021). The article confirms the stratigraphy as described above and mentions that the soil below the Pleistocene consists of alternating clay, silt and (fine) sand with a relatively low cone resistance. The foundation design for the Zalmhaven tower resulted in 162 piles of 0.95 m diameter and 65 m length. Since the new CPTs are not available in Dinoloket, a location very close to the tower was taken for the purpose of elaborating this example.

Based on the selected CPT000000081624, the parameters of the HSsmall model for the various soil layers were automatically determined using paths of correlations in APD. This procedure is described in more detail by Van Berkom et al. (2022). As an example, Table 2 shows the parameters of the medium dense sand layer between 18 m and 28 m depth. The relative density of this layer was (automatically) determined as 68.8%.

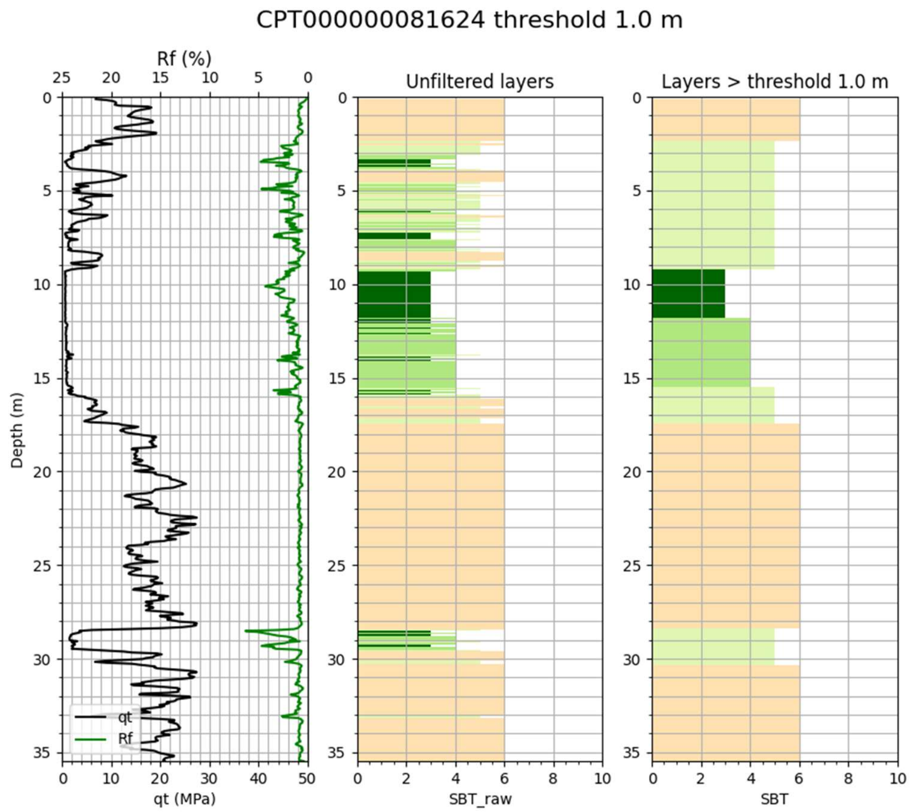

Figure 2: Automatic CPT interpretation from APD

Left: cone resistance and friction ratio as a function of depth
Middle: interpretation of individual CPT readings (here every 5 cm) to SBT
Right: SBT of different layers after stratification, considering minimum layer thickness

Table 2: Parameters of the HSsmall model for the sand layer at 18-28 m depth

Parameter	Value	Unit
γ_{unsat}	17.75	kN/m^3
γ_{sat}	20.08	kN/m^3
E_{50}^{ref}	41280	kN/m^2
E_{oed}^{ref}	41170	kN/m^2
E_{ur}^{ref}	123800	kN/m^2
G_0^{ref}	130500	kN/m^2
γ_{07}	$1.312 \cdot 10^{-4}$	-
p^{ref}	100	kN/m^2

Power	0.5124	-
c'	0	kN/m^2
φ'	38.19	°
ψ	6.113	°
ν_{ur}	0.2	-
K_0^{nc}	0.4706	-
R_f	0.9140	-

5.2 Surface elevation data

The AHN database indicates that the ground surface at the target location is NAP +3.4 m (source: ahn.nl; NAP = Normaal Amsterdams Peil = Dutch reference level). This is consistent with the ground surface elevation obtained from the CPTs. The ground surface is more or less horizontal; therefore, it is not necessary to obtain a more detailed digital terrain model.

5.3 Creation of underground model

The automatic interpretation of CPTs resulted in 18 ‘boreholes’ that were stored in a combined CSV file, and this file was read and visualized in Leapfrog (Figure 3). Figure 3 seems to show only 12 boreholes, but it turned out that some identical CPTs were stored in Dinoloket under different names, and they overlap in the figure. These were not filtered out here since it does not make any difference in results. The information about the ‘Soil Behavior Type’ in the legend was provided by APD in the CSV file.

Since the same SBT may appear in different layers, it is first necessary to subdivide the SBT in different sub-groups and ensure that similar layers in different boreholes belong to the same sub-group. This process has not yet been automated, but a first and easy step to do this could be based on depth or the ideas of Rauter & Tschuchnigg (2022) could be implemented.

The next step is to create a geological model by combining all sub-groups of layers. The result is shown in Figure 4, in which the layer volumes are rendered semi-transparent such that the boreholes are still visible. The geological model ensures that the layer volumes are consistent. Besides the layer volumes, the geological model generates the boundaries between the layers as triangulated surfaces.

The entire model is stored in the cloud via Seequent Central. In the case additional data (boreholes, surface elevation data, etc.) become available, the geological model is automatically updated to incorporate and reflect the new data.

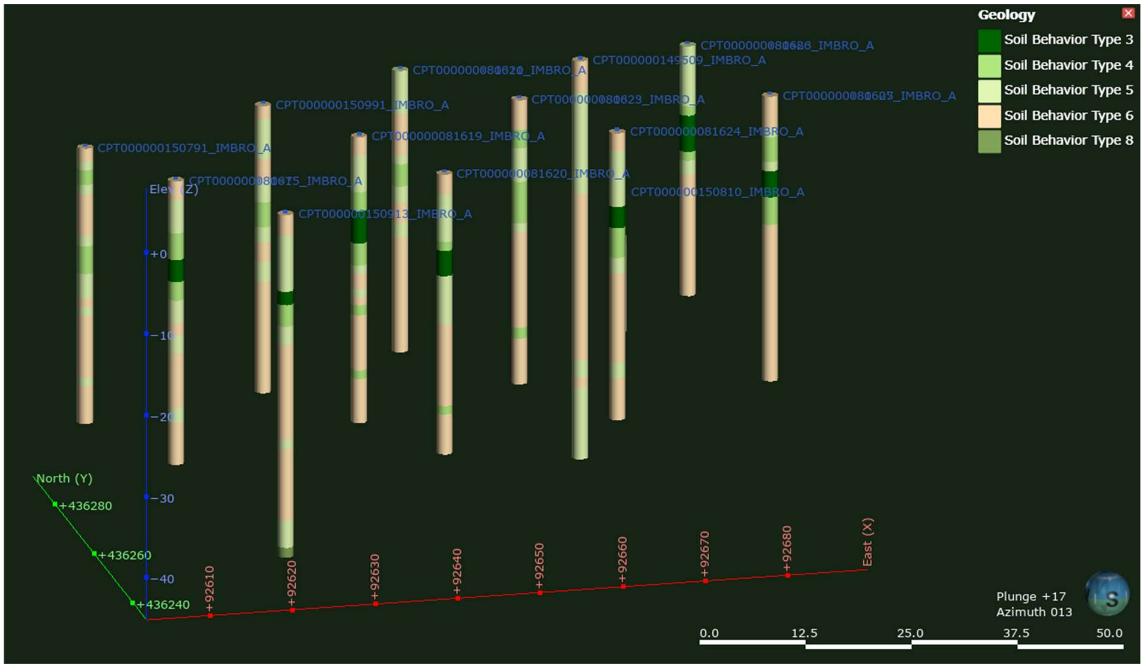

Figure 3: Visualization of ‘boreholes’ (from CPTs)

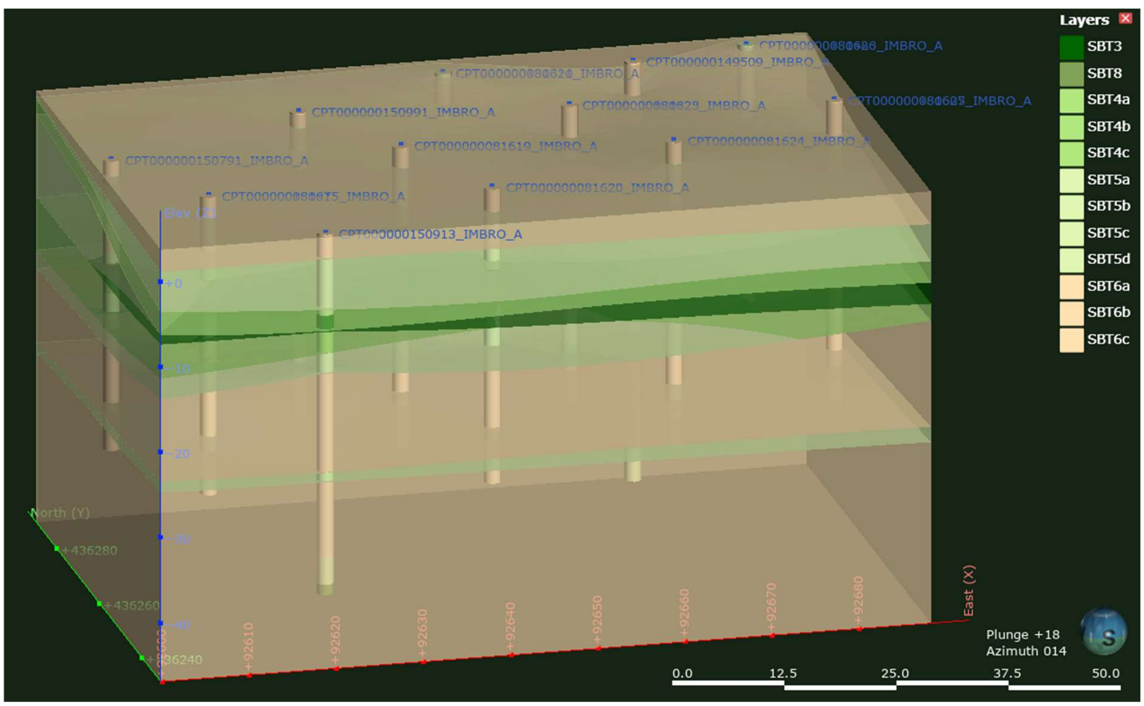

Figure 4: Visualization of soil layers based on sub-groups of SBTs

5.4 Creation of finite element model

As a next step, the layer boundaries are exported from the geological model to PLAXIS 3D. This is currently done via DXF files, but in the future, this can be done directly via Seequent Central. In addition, the parameter sets as generated by APD are also available. After intersecting the layer boundaries to generate the soil volumes, the parameter sets are assigned to the corresponding soil volumes. In this way, the soil layers are recreated in accordance with the geological model. In fact, the geometric model as well as the model parameters are all based on the CPTs interpreted by APD. Figure 5 shows the results.

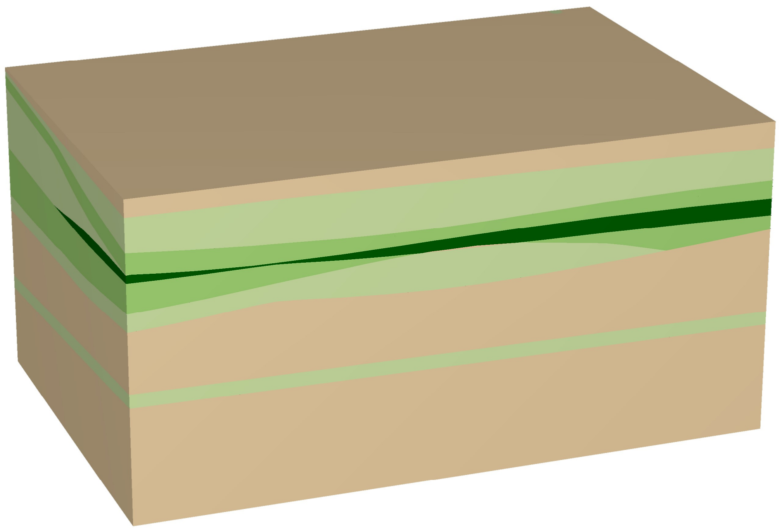

Figure 5: Geometric model in PLAXIS 3D

Finally, Figure 6 shows the finite element mesh that was automatically generated from the geometric model. The mesh shows some badly shaped elements, which are inherently related to thin (sub-)layers. This is still a point of attention for further improvement.

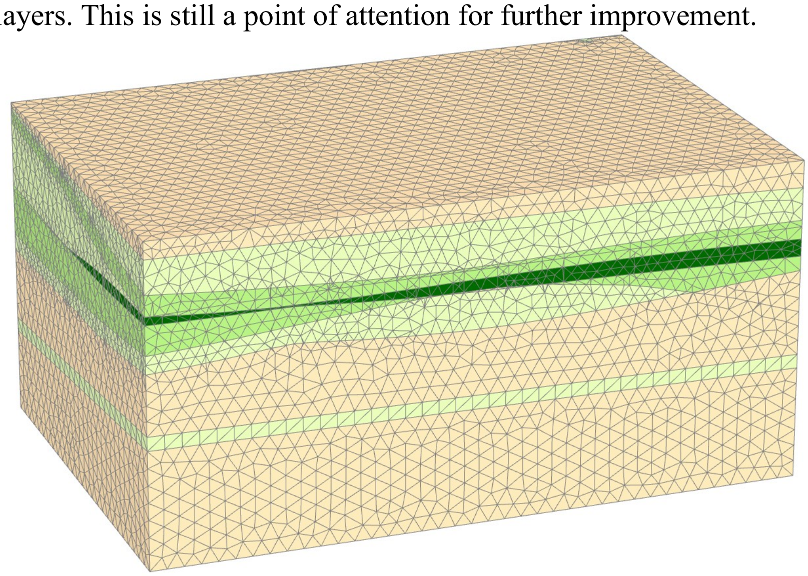

Figure 6: Finite element model

Considering the application programming interface (API) as available in PLAXIS, most of the above steps can be automated by means of an external Python program. This has only been done to a limited extent here and will be part of continuing developments.

5.5 Other possible applications

The previous example demonstrates how automation can be used to create a 3D underground model to facilitate 3D finite element modelling in a Digital Twin environment. The example is typical for a project in an urban environment on a horizontal ground surface.

Analysing the stability of embankments, dams or slopes would require additional surface elevation data to be included in the underground model. These data are often publicly available in the form of point clouds, grids or triangulated surfaces.

An example of a geological model in which ground surface elevation data has been included is shown in Figure 7.

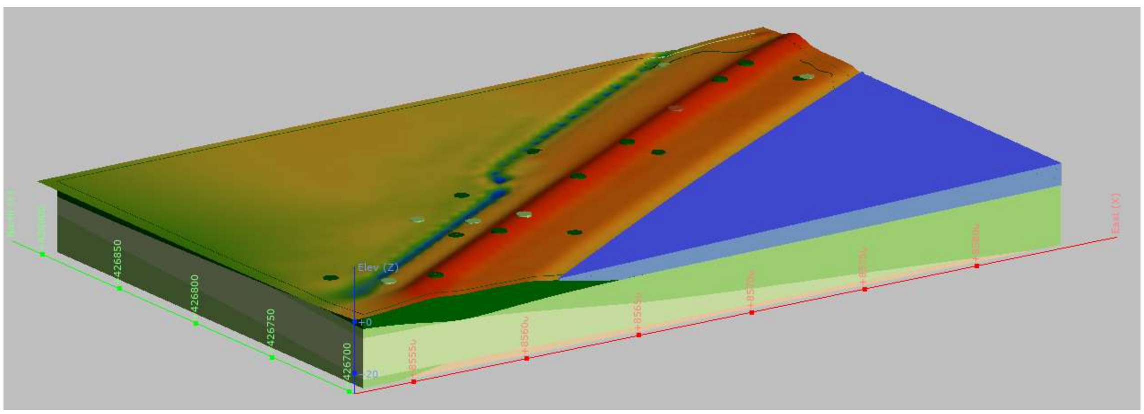

Figure 7: Underground model with surface elevation data involving a river embankment

A 3D geological model related to existing 'line infrastructure' (road, railway, river embankment (dike, levee), pipeline or tunnel) can be used to take multiple 2D cross sections for an (automated) finite element-based analysis of settlement, deformation, stability and structural integrity. The way corresponding 2D finite element models are created is similar as what was described for the 3D model in the above example, but only based on the exported / imported cross section data. An automated procedure could facilitate the responsible authorities to check the infrastructure's safety under changing (climate) conditions (for example: sea level rise, increased river discharge, increased precipitation, periods of drought; increasing traffic, heavier trucks and trains, higher train speed or frequency, etc.).

6 Conclusions

Advanced and automated software solutions can facilitate our continuous drive for more efficiency in geotechnical engineering and the collaboration with related disciplines and stakeholders. The article demonstrates how automated parameter determination (APD) based on cone penetration test (CPT) data can encourage and improve numerical modelling in a Building Information Modelling (BIM) or Digital Twin environment. Especially in an early stage of a project, when limited soil data are available, CPTs can be very useful to automatically create an underground model and to derive model parameters for preliminary 2D and 3D finite element analysis. In addition, ground elevation data may be needed to complete the underground model in the case of a non-horizontal ground surface at the project location.

For existing infrastructure in a Digital Twin environment, new data can be taken into account easily and the models can be updated automatically to include the new data or to account for changing conditions.

An example was elaborated in which a complete finite element model was generated for a location near the Zalmhaven tower in Rotterdam. The data for this example was taken from publicly available sources in The Netherlands.

The current state of development only involves a partially automated workflow, but the ideas presented herein would allow, in principle, for full automation of numerical modelling and finite element analysis. It is important to emphasize the role of the geotechnical engineer as the one who remains responsible for what the system creates and produces. This requires transparency and the possibility to interfere, check and adapt in the various steps of the process.

At the same time, an automated system of parameter determination can help reducing the spread in results when different engineers solve the same geotechnical problem. Thereby, it can contribute to the confidence in the use of advanced numerical tools for geotechnical design.

References

[1] Benz T. (2007): Small-strain stiffness of soils and its numerical consequences. PhD thesis. Heft 55, Institut für Geotechnik, Universität Stuttgart.

[2] Brinkgreve R.B.J., Engin E. and Engin H.K. (2010): Validation of empirical formulas to derive model parameters for sands. In: Benz T. & Nordal S. (eds.), Numerical Models in Geotechnical Engineering, NUMGE 2010. Leiden: CRC press, 137-142.

[3] Brinkgreve R.B.J. (2019): Automated model and parameter selection: Incorporating expert input into geotechnical analyses. *Geostrata* 23(1), 38-45.

[4] Kulhawy F.H. and Mayne P.W. (1990): Manual on Estimating Soil Properties for Foundation Design. EPRI EL-6800, Project 1493-6. Palo Alto: Electric Power Research Institute.

[5] Marzouk I., Tschuchnigg F., Paduli F., Lengkeek H.J. and Brinkgreve R.B.J. (2022): Determination of fine-grained soil parameters using an automated system. In: Gottardi & Tonni (eds), Cone Penetration Testing 2022. Taylor & Francis, 540-545.

[6] NEN (2016): Nederlandse Norm NEN 9997-1, Geotechnisch Ontwerp van Constructies. Delft: Nederlands Normalisatie Instituut.

[7] Rauter S. and Tschuchnigg F. (2022): Identification of soil strata from in-situ test data using machine learning. In: 16th Int. Conf. of the International Association for Computer Methods and Advances in Geomechanics, IACMAG 2022.

[8] Robertson P.K. (2009): Interpretation of cone penetration tests – a unified approach. *Canadian Geotechnical Journal* 46(11), 1337-1355.

[9] Robertson P.K. (2010): Soil Behaviour Type from the CPT: an update. In: 2nd Int. Symposium on Cone Penetration Testing, Huntington Beach, USA, Vol. 2. 575-583.

[10] Robertson P.K. (2016): Cone penetration test (CPT)-based soil behaviour type (SBT) classification system - an update. *Canadian Geotechnical Journal* 53(12), 1910–1927.

[11] Schweiger H.F. (2002): Results from numerical benchmark exercises in geotechnics. In: P. Mestat (ed.), 5th European Conf. Numerical Methods in Geotechnical Engineering. Paris: Presses Ponts et chaussees, 305-314.

[12] Schippers R.J., Bijnagte J. and Van Tol A.F. (2021): Geotechnisch ontwerp van De Zalmhaven te Rotterdam (deel 1). *Geotechniek*, jaargang 25, No. 3.

[13] Seequent (2022): Leapfrog Works Version 3.1 – User Manual. Christchurch: Seequent Limited.

[14] Storteboom O., Woollard M. and Verhagen J. (2022): Efficiency examined of hands-free Cone Penetration Testing using the SingleTwist® with COSON. In: Gottardi & Tonni (eds), Cone Penetration Testing 2022. Taylor & Francis, 229-234.

[15] Van Berkom I.E. (2020): An automated system to determine constitutive model parameters from in situ tests. MSc thesis. Delft University of Technology.

[16] Van Berkom I.E., Brinkgreve R.B.J., Lengkeek H.J. and De Jong A.K. (2022): An automated system to determine constitutive model parameters from in-situ tests. In: Rahman & Jaksa (eds), 20th Int. Conf. on Soil Mechanics and Geotechnical Engineering. Sydney: Australian Geomechanics Society, 329-334.

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