Use of a 3D stratigraphic model as tool for improved communication and risk assessment in large infrastructure projects

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Abstract. As more work processes are moving into the digital space, such as collaborative BIM environments, the toolbox of the geotechnical engineer needs an update to efficiently keep track. Visualization of soil conditions in 3D space, using implicit modelling tools, is rapidly changing how geotechnical engineers engage with digital data. For a large railroad development in Norway, a 3D stratigraphic model is developed to act as a hub for soil interpretation, decision making and communication of geotechnical challenges and risks. Lithology is interpreted from all geotechnical boreholes and used as basis for the model together with a terrain model from GIS. The model is dynamically updated as new geotechnical soil investigations are performed and is actively used in the geotechnical design work. Overall, the 3D stratigraphic model is successfully applied for: (1) Visualization of geotechnical uncertainty with a classification based on radial distance to the borehole, (2) communication of sub-surface conditions and risk to project stakeholders and (3) efficiently exporting cross-sections as basis for geotechnical analysis.

1. Introduction

The ability to effectively communicate and make understandable geotechnical information and risk to all project stakeholders (engineers, architects, clients, contractors and authorities) is a central challenge for geotechnical engineers. All underground facilities interact in some way with the data and interpretations of the geological, geotechnical and hydrogeological conditions at site. When not sufficiently accounted for, especially during the early design phase, these uncertainties may cause significant time delay and cost increase in the further course of the project.

Given the current trend of growing civil engineering projects, both in scope and complexity, there is need to improve the geotechnical toolbox. Also, the introduction of BIM requirements for infrastructure projects is changing how underground data and models are created and managed. A modern BIM workflow for the geotechnical engineer involves continuous refinement and updates of 3D models as more and more data are collected and interpreted throughout the project life-cycle. Such workflow requires dynamic and rapid modeling software’s.

For a large railroad development outside the Norwegian capital Oslo, a 3D stratigraphic model is created as a basis for decision making and improved communication towards internal and external stakeholders. At the same time, it provides increased efficiency and availability of the geotechnical information.
2. Developing the 3D stratigraphic model

2.1. Principles of modelling

A 3D ground model can be created using different modelling techniques. Explicit modelling is fundamentally based on drawings, where 2D elements such as stratigraphic cross sections are joined together in a 3D space. An example of a large infrastructure project adopting the explicit modelling technique was the Crossrail project in London [4].

Another method for modelling relies on interpolating the data to regularly spaced 3D grid nodes (voxels) and then either viewing the data with a volume visualization software, or by converting the voxels into isosurfaces [6]. This approach may be cumbersome for projects of large spatial extent as the number of voxel cubes required to represent the ground in high detail becomes impractical. Also, the interpolation process may require a geostatistical study of the data, i.e. variography, which may be very time-consuming.

A third method, which is the method adopted for the 3D stratigraphic model created in this work, is Implicit modelling. This approach relies on interpolation algorithms to construct a model based on a combination of measured data and user interpretation. Implicit modelling allows for fast and dynamic management of a 3D ground model in an iterative workflow. Some key advantages include the possibility to rapidly evaluate large quantities of data and to interpolate smooth surfaces using geostatistical methods [2]. Several authors ([5] and [11]) have recently published examples of how implicit modeling in civil engineering projects may be adopted.

Such a software utilizing the implicit modelling approach is Leapfrog Works. This software enables the construction of geological 3D models using a bi-harmonic radial basis function (RBF), a form of volumetric spline interpolation. In contrary to invariably local interpolation techniques, such as kriging, the RBF is a global interpolation method and is dependent, and snaps on to, on all data points [3].

![Figure 1. Data input to the 3D stratigraphic model and philosophy of using the model as focal point for geotechnical data and decision making on the project.](image-url)
2.2. Bringing data together to create a model

The basic input to the stratigraphic model, as shown in figure 1, is mainly geotechnical boreholes coming from a variety of different sources. In case of establishing an early baseline model when no project specific boreholes exist yet, a good start is to check public databases such as the National database for ground investigations (NADAG) in Norway. Unfortunately, NADAG is not a complete database with borehole data from all previous projects. To begin with, some data acquisition from the local municipality, stakeholders or other consulting engineering firms may be necessary. Another data source to implement would be geophysical investigation data. Figure 1 shows some of the main datasets that make up a complete 3D stratigraphic model and how the model acts as a central hub for design and geo-related decision making.

Stratigraphic interpretations are performed for each borehole – diversifying lithology based solely on in-situ soundings or if also piston core samples that were tested in the geotechnical laboratory. A commonly used software in Norway for borehole management is Geosuite Presentation. This software allows for storage and plotting of in-situ soundings such as the Norwegian total sounding, rotary pressure sounding and CPTU. However, there is currently a dire need to update and modernize how geotechnical data is managed, stored and exchanged, as further discussed in the following section.

For the stratigraphic model presented in this paper, the interpretations were manually by first drawing soil layers, see figure 2, then digitizing the data for each borehole in an excel spreadsheet as shown in table 1. This is a rather tedious process however it allows for easy quality assurance and discussion on the interpretations made, prior to setting up the model. Quality assurance of the borehole stratigraphic interpretation is important and a factor which is easily forgotten when the boreholes are later visualized in 3D-space.

Guidelines on how to interpret soil type based on the Norwegian total sounding and rotary pressure (RP) sounding is given in [7]. For soil classifications based on CPTU, using updated soil behavior type charts as proposed by [9] may provide interpretation guidance.

Table 1. Lithology table digitized from interpretation of in-situ soundings and lab tests, where available.

| BH | From (m) | To (m) | Interpretation   |
|----|----------|--------|-----------------|
|  1 |  0       |  3.4   | Topsoil         |
|  2 |  3.4     |  6.7   | Clay            |
|  3 |  6.7     | 17.3   | Quick Clay      |
|  4 | 17.3     | 19.1   | Sand/Gravel     |
|  5 |  0.0     |  6.0   | Topsoil         |
|  6 |  6.0     |  9.0   | Clay            |
|  7 |  9.0     |  9.7   | Sand/Gravel     |
|  8 |  0       |  4.8   | Topsoil         |
|  9 |  4.8     |  9.0   | Clay            |
| 10 |  9.0     |  21.6  | Quick Clay      |
| 11 | 21.6     | 22.95  | Sand/Gravel     |
| 12 |  0       |  5.2   | Topsoil         |
| 13 |  5.2     |  8.7   | Clay            |

Figure 2. Typical plot of a Norwegian total sounding, and a lithology table as listed in Excel prior to import in Leapfrog Works. (T=topsoil, L=clay, KL=quick clay, M = moraine).
The 3D stratigraphic model also require input such as terrain surface and a bedrock surface to do the RBF interpolation and creating 3D volumes of the soil units. The terrain surface is often obtained from a public digital terrain model in the early stages of the project and then, if necessary, revised later with new Lidar/drone scans. The bedrock surface is most commonly generated using total sounding results where the operator has drilled 3 m into bedrock. Alternatively, geophysical methods such as airborne electromagnetic (AEM) scanning are increasingly used on linear infrastructure projects to create large-scale bedrock surfaces [8], even before a single borehole has been drilled.

The most common types of geotechnical soil investigation methods in Norway are the total sounding method, RP sounding method, CPTU and 72/54 mm piston core sampling. Both sounding methods are relatively inexpensive and fast, however in most cases they yield the lowest quality of stratigraphic interpretation due to the limitations in the method itself. Pressure is measured in a load cell at the top of the drill string, and therefore, drill string friction may accumulate and make up a large portion of the overall pressure measured downhole.

As shown in figure 3 for the current project, almost 90% of the boreholes were only investigated using total or RP soundings, making the interpretations from these boreholes a major contributor when creating the 3D stratigraphic model.

2.3. Sharing between software platforms

As more and more of the industry is heading towards digitalization, easy sharing of data through common and structured file formats among software vendors is crucial. It also helps reduce time-consuming data conversion and processing tasks in the day-to-day work of the geotechnical engineer. Non-proprietary data formats, such as the Industry Foundation Classes (IFC) is aiding in this transformation, however a full classification system for underground objects is not ready yet.

![Figure 3. Illustration of the borehole distribution for the current project and the trade-off between uncertainty and cost for soil investigations.](image-url)
Introduction of standardized data structures and code systems for underground objects is important to facilitate model sharing and enabling drawing-free projects. Initiatives such as the development of CoClass for underground objects [10] is a step in the right direction. This system, when launched, aims to give all geo-related underground objects a certain code, allowing all systems in the infrastructure process to identify that specific object (i.e. a bedrock surface). The CoClass hierarchical classification system (coclass.byggtjanst.se) is a Swedish initiative built on the international ISO 12006-2 standard and is supported by the Building Smart Organization. There is also work ongoing to extend the AGS data exchange format to include interpretation and ground model data [1].

Data information should flow freely from e.g. a GIS software to the 3D stratigraphic model and then back again, to fully utilize the potential of each software platform. As example, a public digital terrain model, a WCS layer with 10m resolution, may be imported from GIS into Leapfrog Works as a georeferenced image file and applied as the terrain surface in the stratigraphic model. Later, a soil thickness grid can be computed and exported from the stratigraphic model and directly imported into a GIS software for visualization in the 2D plane as shown in figure 4. Such kind of seamless data transfer enables a highly efficient communication and distribution channel for geotechnical knowledge.

![Figure 4. Georeferenced soil thickness raster from the stratigraphic model, here visualized in a GIS software (red/orange = deep, green/cyan = shallow).](image)

3. The power of visualization

3.1. Visualization of geotechnical uncertainty

Effectively communicating geo-spatial uncertainty to project stakeholders is often a challenge. A 3D stratigraphic model may highly improve this ability through the power of visualisation. Several factors influence the uncertainty of soil and geology represented in 3D space.

Soil deposition history within the project area changes quite rapidly due to the presence of a large terminal moraine named Raet. This terminal moraine was deposited during a temporary halt during the withdrawal of the large glacier covering Norway in the period of Younger Dryas. In addition, the
complexity and uncertainty of the stratigraphy is further increased due to the presence of small and large pockets of quick clay.

One of the most visually striking effects of communicating uncertainty is by showing both the 3D volumes and the borehole locations within the same model, as shown in figure 5. Opacity of the soil units is reduced to enable a see-through of the entire model and to show where in the model the boreholes are located.

![figure 5](image.png)

**Figure 5.** The full 3D stratigraphic model created using the software Leapfrog Work, here with a slice through the model showing the cut-and-cover tunnel design, bedrock surface and borehole collars. Red = quick clay, blue = clay.

Another way to visualize uncertainty is by performing a classification of the soil units based on the distance to the nearest borehole. As shown in figure 5, the model extent is limited to a radial distance of 100 m around each borehole. Each stratigraphic unit (e.g. clay) is further divided into three sub-units to provide a qualitative description of certainty within that unit, this is visualized in figure 7.

As detailed in table 2, the strength of the soil unit color in the model indicates the stratigraphic certainty. Between 0 – 5 m from a sounding the 3D stratigraphy is said to be certain and this is visualized by the colouring. Similarly, the layering is described as uncertain and very uncertain between 5 – 25 m and 25 – 100 m from a sounding.

Different factors contribute to borehole and model uncertainty and some examples are illustrated in figure 6. Such uncertainties should be assessed for each individual project to determine the required visualizations. There is a high potential for further work related to this topic.

**Table 2.** Classification of model uncertainty based on radial distance from borehole.

| Unit         | Certain (< 5 m from borehole) | Uncertain (5 to 25 m from borehole) | Very uncertain (25 to 100 m from borehole) |
|--------------|-------------------------------|-------------------------------------|------------------------------------------|
| Water        |                               |                                     |                                          |
| Topsoil      |                               |                                     |                                          |
| Sand / gravel|                               |                                     |                                          |
| Clay         |                               |                                     |                                          |
| Quick clay   |                               |                                     |                                          |
3.2. Communication with project stakeholders

One major benefit of creating a 3D stratigraphic model is the ease of communication for which it allows, both internally with colleagues and externally towards partners, clients and others. Using the ability to slice through the model allows to rapidly gain an understanding of the stratigraphy and how different soil layers are spatially distributed.

In meetings, the model acts as a focal point for discussion and decision making. Sharing the model among the design team also reduces ambiguity and enables cross-disciplinary collaboration. Visualization of the model uncertainty, e.g. by reducing the opacity of the soil volumes as function of distance from the borehole, helps to increase understanding when communicating geo-related risks.

As shown in figure 5 and figure 8, project designs are easily imported in the model and co-visualized with the soil. When using a slicing plane to see through the model, here with reduced opacity on the soil volume layers, it is possible to navigate the entire model seamlessly. This allows for rapid quality assurance on cross-discipline models against the stratigraphic model. The 3D stratigraphic model may also be exported for use in collaborative BIM environments.
4. 3D stratigraphic model as baseline for geotechnical analysis

When the borehole interpretations are quality assured, and the stratigraphy is finally modelled in 3D space, it is possible to generate sections for export in a DXF format. This is a common, and open, exchange format for CAD files and supported by most geotechnical analysis software's. Multiple cross-sections, either drawn by hand or following an alignment with a set spacing as shown in figure 8, may rapidly be exported to perform e.g. a plain strain limit-equilibrium stability analysis. The entire 3D model may also be exported in DXF format for import to e.g. Plaxis 3D. Due to the ability to dynamically update the 3D model, the workflow of re-exporting updated cross sections is efficient.

Figure 9 shows an example of a cross section from the 3D stratigraphic model. When new borehole data is added to the model, all cross sections are automatically renewed. This reduces the time spent manually redrawing each cross-section and comparisons can quickly be conducted to check for changes.

As many cross sections are automatically generated from the model it is easy to identify and select the most critical ones for further geotechnical analysis. Also, since the sections can be imported directly into many standard analysis applications, compliance between the stratigraphic model and the geotechnical analysis is ensured. This also allows for more thorough geotechnical evaluations to be done and a larger amount of cross sections may be evaluated in a rather short amount of time.

5. Summary

Introducing a 3D stratigraphic model into the geotechnical workflow for large infrastructure projects have resulted in several key improvements. The model was successfully applied for: (1) Visualization of geotechnical uncertainty with a classification based on radial distance to the borehole, (2) communication of sub-surface conditions and risk to project stakeholders and (3) efficiently exporting cross-sections as basis for geotechnical analysis and merging them with models from other disciplines.

Adopting more digital ways of using and communicating geotechnical information allows the discipline of geotechnical engineering to be better equipped to meet future challenges. As projects become increasingly more complex and reliant on cross-discipline collaboration, the 3D stratigraphic model is a useful addition to the geotechnical toolbox.
Figure 9. Cross section with soil layers from the 3D stratigraphic model, ready for DXF export, further geotechnical analysis and reporting. Note that also water as a volume is modelled on the right side.

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