Contribution of 3D model representation in subsurface geotechnical investigations

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Abstract

3D model representation is important in enhancing geotechnical site characterization. It was initially widely used in geologic investigations. Due to its increasing demand in geotechnical engineering, there has been an upsurge in its application in subsurface investigations. Similarly, more dedicated software are being developed to support application demands. This study reviewed progress of 3D modelling in geotechnical investigations including current practices and opportunities for improvement. It showed that 3D modelling of geotechnical investigations has been popularly used in subsurface risk assessment, visualization, and identification of important target sections or occurrence of resources such as quarry materials, groundwater, or hard stratum. These applications are supported by numerous standalone software or add-on computer scripts or packages. However, most software are still lacking some important functionalities such as uncertainty assessment. Independent computer scripts seem to break this limitation but still need more improvements and wide application. An example of this application was shown in a case study in Mombasa Kenya, where 3D modelling potential was used to identify weak subsurface sections, 3D visualization, and identification of groundwater in a project site for construction of an inland container depot.

Keywords: ***software, 3D model, geotechnical investigations, data processing***

1. Introduction

Geotechnical investigation is normally carried out to assess site suitability for construction of a proposed project. It helps to determine the strength and behaviour of the ground and construction materials and to analyze potential risks to the proposed construction (Bo, 2022; Look, 2007). Subsurface investigation focuses on uncovering buried characteristics beneath the surface through inversive methods (such as drilling, excavation trenches/pits, etc.) or non-inversive methods such as sounding s or a combination of both methods (Hunt, 2007). Inversive methods provide direct actual measurements or observations in narrow openings through the subsurface profile. They also allow subsurface sampling for further laboratory testing and analysis. Hence, they are traditionally preferred even though they are cumbersome and cover only limited discrete points in a proposed project site (Longoni et al., 2012). This article illustrates how they have been or can be enriched to improve their representation of geotechnical properties of a construction site.

Methods for subsurface geotechnical investigations have evolved over the years. The most prominent old technique was the digging of pits and trenches to access soil and rock features below the surface (Griffiths, 2014; Hool and Kinne, 1923). This method was improved by the advent of the drilling technology. This technology improved the efficiency and depth of digging in response to the increasing demand for space for urban growth, infrastructure development, resource exploration, and waste disposal (Brady et al., 2017; Reiffsteck et al., 2018). Instrumented and smart drilling have further improved the drilling technology (Alqadad et al., 2017). Furthermore, integrated application of drilling technology and non-inversive methods such as geophysical sounding and remote sensing have made tremendous improvements in subsurface investigations (Devi et al., 2017; Sulistijo and Anwar, 2013). There are still challenges with data handling that is commensurate with advances in equipment for subsurface investigations. This study reviewed opportunities for data handling to improve subsurface characterization of geotechnical properties.

Subsurface geotechnical investigations are not without challenges. The challenges often encountered include inaccurate equipment, heterogeneity of target site, presence of underground utilities (e.g., pipes, electrical lines, etc.), variable fill material, groundwater flow, weather conditions, and site access and safety (Otake and Honjo, 2022; Zhang, 2011). There are also data challenges particularly in sample selection prior to investigation, data mining, and visualization of the final investigation outcome. Data handling challenges are also observable in situations involving integrated use of different equipment, equipment generating large data, and time-series data (El Sibaii et al., 2022, 2022). Recent developments in building information modelling (BIM), GIS, and statistical modelling software have helped to improve efficient and accurate geotechnical data handling (Bui et al., 2016). This paper reviewed advancements in geotechnical investigation data representation with particular focus on three-dimension (3D) data management.

Inversive subsurface geotechnical investigations are mostly given in one-dimensional (1D) representation known as borehole log. The log shows properties of soil and rock materials down the vertical profile (Hunt, 2007; Wang et al., 2022). Although 1D representation of geotechnical investigations is reliable because it contains primary observations/measurements at the sampled locations, it does not show spatial variations between observation points in a project site. Subsurface geotechnical conditions in most project site are naturally varied, which require many spatially located observation locations for adequate characterization (Caballero et al., 2022). Geographic Information System (GIS), geostatistics and non-inversive investigation methods have been used to overcome the limitations of 1D borehole logs (Awan et al., 2022; Liu et al., 2023; Orhan and Tosun, 2010). These 2D approaches have a better representation of spatial variations of geotechnical properties. They can portray spatial variations either in a vertical plane (such as in cross-sections) or horizontally across the landscape. Three or more dimensional visualization is the ultimate representation since it combines both vertical and horizontal dimensions in one illustration (Dong et al., 2015; Hack et al., 2006; Petrone et al., 2023). This paper analyzed the potential of 3D modelling in subsurface geotechnical investigations.

2. 3D Modelling Of Geotechnical Investigations

Three-dimensional representation of geotechnical investigations is an illustration of a volumetric cross-section of the target site. It should show 2D variations of the geotechnical properties in an x-y plane either at each sampling depth (Figure 1a) or at each sampling transect (Figure 1b). The 3D model is an ensemble of the 2D maps in a project site (Figure 1c). Different approaches have been proposed in the literature for developing 2D maps and 3D models.

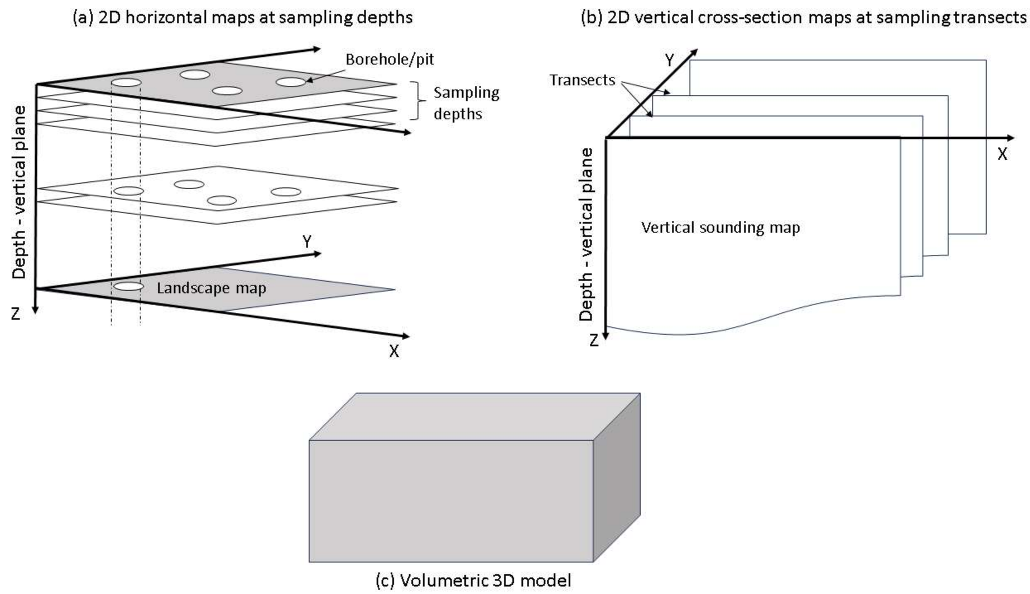

Figure 1: Concept of 3D model for subsurface geotechnical investigations

2.1 Approaches for 2D maps of subsurface geotechnical investigations

2D map of geotechnical properties gives a cross-sectional slice of the subsurface. The slice is either vertical down the profile or horizontal across the landscape (Figure 1). The vertical cross-section produces a snapshot of subsurface stratigraphy from top (surface) to the bottom. This type of cross-section is mostly produced by the geophysical sounding approach (Azrief Azahar et al., 2019; Romero-Ruiz et al., 2018; Tsai and Lin, 2022) or series of borehole/excavation pits a long a transect line (Guan and Wang, 2021) (Table 1). Geophysical approach uses electric, magnetic, sonic, radio, or seismic signals to determine orientation, depth, and geotechnical characteristics of earth materials within range of the signals. The signals are either emitted and recorded by specialized instrument(s) or are naturally emitted from the earth and recorded by the instruments (Chandran and Anbazhagan, 2017). 2D vertical cross-sections are used to determine orientation and depth of subsurface strata, location of cavities or variation in strength of subsurface strata, thickness of strata, potential underground hazards to construction project, changes in geotechnical properties with subsurface depth, among others (Medhus and Klinkby, 2023; Paillet and Saunders, 1990; Soupios et al., 2007). They are also suitable for evaluating risk to existing foundations. Despite their importance in subsurface characterization, vertical cross-sections are limited to the transect line or excavation boreholes/pits in which they are developed. Resultant maps from the cross-section are assumed as representative of the entire project site, which can be a source of uncertainty when characterizing the entire construction site.

Table 1: Approaches for 2D mapping of subsurface geotechnical characteristics

Cross -section	Approach	Techniques	Reference
Vertical	Geophysical sounding	Seismic	(Bačić et al., 2020)
		Potential (Gravity, electric, magnetic, etc)	(Dezert et al., 2019)
		Electromagnetic	(Auken et al., 2017)
		Sonic	(McNally, 1990)
	Drilling/Excavation	Borehole, Pit excavation	(Hunt, 2007)
Horizontal	Drilling and GIS	Geostatistics	(Pinheiro et al., 2018)
	Remote sensing	Satellite	(Chen et al., 2016)
		Ground Penetrating Radar	(Siggins, 1990)
		Electromagnetic Induction	(Pellerin, 2002)

The horizontal cross-section of the subsurface portrays a stratum layer at a given depth. It's produced by mapping spatial distribution of many observations in the project site or through remote sensing techniques such as satellites, aerial photographs, and proximal sensing (Table 1) (Liu et al., 2016; Von Hebel et al., 2014). Most Geographic Information System (GIS) approaches depict this type of cross-section when they map geotechnical properties of the site at a given depth. This approach uses geostatistical methods to integrate observations at discrete locations to produce maps of the geotechnical properties (Ahmed et al., 2020; Aldefae et al., 2020; El-Banna et al., 2023; Labib and Nashed, 2013).

2.2 Approaches for 3D model for subsurface geotechnical investigations

A 3D model for geotechnical investigations endeavors to integrate both vertical and horizontal cross-sections of a project site into a volumetric solid representation of subsurface geotechnical conditions. It's increasingly being demanded in geotechnical investigations since it portrays a complete subsurface ground condition more than 1D or 2D representations (Kahlström et al., 2021; Petrone et al., 2023). Three approaches are available in the literature for developing 3D models for geotechnical investigations: 1) modelling of geotechnical interfaces, 2) fusion of 2D layers in a GIS, and 3) three-dimensional geotechnical objects (Table 2).

Table 2: Approaches for 3D modelling of geotechnical investigations

Approach	**Method**	**Reference**
Geomodelling of geotechnical interfaces	Surface mesh generation	(Frank et al., 2007)
	Planar mesh and interpolation	(Mallet, 1997)
Fusion of 2D layers	Machine learning	(S. Wu et al., 2021)
	Geostatistics and GIS	(Kim et al., 2020)
	Sequential gaussian simulation	(Aghamolaie et al., 2019)
	Finite element	(Hemeda, 2019)
3D geotechnical objects	Building Information Model	(Satyanaga et al., 2023)
	Wireframe and voxel	(Moore and Johnson, 2001)
	Intersection of triangulated surfaces	(Elsheikh and Elsheikh, 2014)
	Volumetric solid model	(Lemon and Jones, 2003)

Approaches such as geo-modelling of geotechnical interfaces and building of 3D geotechnical objects are mostly geological methods popularly used by geologists in large projects. They have been used in large-scale hydrogeologic frameworks for groundwater, geologic hazards, mineral exploration, etc. (X. Wu et al., 2021). (Ozmutlu and Hack, 2006) have also shown their application in feasibility studies for subsurface stability in landslide-prone areas. However, they are not so popular in geotechnical engineering especially in small projects and where input geotechnical observations are few (Mei, 2014). Moreover, they are currently not adequately amenable to uncertainty analysis. Approaches involving fusion of model elements are the most popular in small-scale geotechnical investigations. They have been applied successfully in small and large projects alike since they integrate geological modelling approaches with GIS and geostatistics of geotechnical observations and discrete locations (De Rienzo et al., 2008; Masoud et al., 2022). Since they include statistical methods, they can also be used to develop uncertainty analysis of the 3D model.

All approaches for 3D modelling of geotechnical investigations involve aspects of data acquisition, data preparation and processing, model testing, and model application (El Sibaii et al., 2022). These four-stage processes differ with geotechnical investigation projects. However, if they are harmonized and standardized then they can be a useful input into the Building Information Modelling (BIM) paradigm. BIM paradigm proposes digital collection and sharing of geotechnical and construction information of projects (Eastman et al., 2018; El Sibaii et al., 2022). Presently, there are no clear standards and harmonization procedures in BIM to support its extension to geotechnical investigations and 3D modelling (Valeria et al., 2019). An initial step to create strategies for BIM-like information management and data-sharing of geotechnical information would be the development of proper data management. This has been observed in the literature and proposition of software for kickstarting the process (Hamman et al., 2017; Lee et al., 1990; Montanari and Previatello, 1979).

3. Software for 3D Modelling

Development of software for modelling geotechnical investigations was originally motivated by the programming progress in the mining and gas exploration sectors. The first attempt of computer aided investigations was an adaptation of the then mining software, which opened the way for more customization (Orlić, 1997). These attempts were mainly software capable of developing 1D or 2D models. The main challenges to quick development of dedicated software for 3D models for geotechnical investigations were: 1) lack of adequate understanding and detailed data for subsurface geotechnical characteristics, 2) demand for geotechnical investigations was still nascent, and 3) there were few experts to mount such a trivial demand (Toll and Barr, 2001). Progress was made with development of software based on finite element method, which is limited in robust characterization of variations of geotechnical properties in vertical and horizontal dimensions. The software have been documented in geotechnical and geo-environmental software directory[1]. Some of these are shown in Table 3, which shows that they are mostly commercially available.

Table 3: Software for 3D modelling of geotechnical investigations

Software	**Visualization**	**License**	**site characterization**	**Other functionality**	**Company**
Subsurface analyst	yes	Commercial	Yes		
Vulcan explore bundle	yes	Commercial			
WLD 3D visualizer	yes	Commercial			
Slide 3D	yes	Commercial		Numerical modelling	Rocscience

[1] http://www.ggsd.com/, accessed on 23 October 2023

Software	Visualization	License	site characterization	Other functionality	Company
Plaxis 3D	yes	Commercial	Yes	Numerical modelling	Seequent
RS3	yes	Commercial	yes	Numerical modelling	Rocscience
Adina		Commercial		Numerical modelling	
Adonis	yes	Open-source		Numerical modelling	
Diana finite element analysis	yes	Commercial	Yes	Numerical modelling	Diana FEA
Irazu		Commercial		Numerical modelling	Geomechanica
Midas GTS NX		Commercial		Numerical modelling	Midas IT
GEMS		Commercial		Numerical modelling	GEMS
TatukGIS		Commercial		Numerical modelling	Tatuk GIS
CESAR-LCPC	yes	Commercial		Numerical modelling	Itech
Versat-P3D		Commercial		Numerical modelling	
Leapfrog Works	yes	Commercial		Data management	Seequent
Oasis montaj	yes	Commercial		Data management	Seequent
Res3DInv		Commercial		Data management	Seequent
HoleBase	yes	Commercial		Data management	Seequent
Geo5	yes	Commercial	Yes	Engineering geology	Fine Software
GST	yes	Commercial		Data management	GiGa infosystem
Map3D	yes	Commercial	Yes		Mine Modelling Pty Ltd
Stress Transform		Open-source		Stress calculation	
AutoCAD Civil 3D	yes	Commercial		Design	Autodesk

Recently, open-source platforms and computer packages have been developed to support wide program or computer script development. They include GIS software, statistical software, and numerical modelling software. They have facilitated the development of numerous add-on packages and open-source scripts for most computer applications in geo-environmental engineering sectors. For example, GemPy, which is a python script, has shown tremendous applications in 3D modelling of subsurface geologic investigations (De La Varga et al., 2019). (Bullejos et al., 2022) also developed a python code for 3D visualization of borehole strata using borehole logs. Many more python scripts have since been produced for soil and rock properties, albeit with focus on geology or groundwater characterization (Rasmussen, 2020; Schorpp et al., 2022).

4. Application Of 3D Models in Geotechnical Investigations

4.1. Risk assessment

Geotechnical investigations for risk assessment can be taken either before or after construction of a project or foundation. Most assessments done before construction have limited restrictions compared to those carried out after construction. 3D models play crucial role in portraying volumetric representation of the subsurface conditions by locating the orientation and magnitude of risk factors such as fault lines, hollow sections, weak strata, presence of utility lines, groundwater potential, etc. They are also suitable in forensic projects where restrictions and precisions are involved. (Marache et al., 2009) used 3D modelling to show infrastructure damage due to differential settlement in France. (Liu et al., 2021)used it to develop geo-hazard monitoring and early warning in China. (Venmans et al., 2015) used 3D modelling approach in the Netherlands to map geotechnical risk for infrastructural works in Deltaic area.

Most applications for risk assessment use dedicated 3D software for geotechnical and geologic modelling. There are very few cases in literature where independent or add-on scripts have been used although they have potential. The scripting approach may be more robust given that they are amenable to manipulation to suit changing characteristics of risk assessment demands. The scripts can be used to integrate geophysical methods and limited drilling to produce the 3D models. (Cueto et al., 2018) used this approach to map subsurface karst sinkholes in Saudi Arabia. The same approach was also used by (Arisona et al., 2020) to map subsurface voids in Kinta Valley in Malaysia.

In the risk assessment applications, 3D models are used to locate depth of the risk from the soil surface and the distance to the construction/foundation. The models also show extent of the risk and danger it poses to the construction.

4.2 Visualization

3D models of geotechnical investigations give a realistic representation of actual orientation of the subsurface characteristics than 1D or 2D models. Hence, they are most suitable where subsurface complexity cannot be adequately represented by 1D or 2D. Through 3D visualization, it is possible to view neighborhood relationships and total number of strata in a project subsurface (Guo et al., 2021). This is particularly important in areas where there is demand for subsurface space utilization and limited land space for horizontal expansion for infrastructure development. In such cases, 3D visualization gives more clarity of available and suitable underground space for expansion of structural development. There are many examples in the literature which have demonstrated these applications. For example, (De Rienzo et al., 2008) used 3D to improve visualization of subsurface characteristics in underground civil planning in Turin, Italy. (He et al., 2023) used 3D visualization to show stratigraphic distribution of a subsurface in Tongzhou in China. A similar approach was also used by (Masoud et al., 2022) to improve visualization of subsurface for urban planning in Medina, Saudi Arabia.

4.3 Location of target points

Geotechnical investigations facilitate identification of target sites and volume of resources such as groundwater, rock, minerals, quarry materials, etc. 3D model helps to illustrate multi-dimensional aspects of these characteristics to improve subsequent engineering designs where they are involved. For example, 3D model can adequately illustrate the depth and extent of hard layers when designing pile foundation (Priya and Dodagoudar, 2017; Touch et al., 2014). Its application in the mining industry has been well practiced over the years (Akiska, 2013; Kaufmann and Martin, 2008). They have also been extensively used in hydrogeologic exploration of groundwater occurrence and impact of groundwater fluctuation to foundation stability (Beygi et al., 2020; Mielby and Sandersen, 2017). (Vanneschi et al., 2014) used 3D modelling in excavation activities such as determination of volume of quarry material at a proposed site.

Although there are successful applications of 3D modelling in the literature for locating subsurface target site and volume of resources, there is no clear information of how these applications incorporate uncertainty analysis. Most applications use software or methods that overlook the importance of uncertainty analysis in the 3D models. It is important to incorporate this aspect into the applications to improve confidence and accuracy of subsequent utilization of the application results.

4.4 Example case study in Mombasa Kenya

3D geotechnical model was developed for a construction project in Kibarani Inland Container depot in Mombasa County in Kenya (Figure 2). 32 boreholes were drilled using motorized percussion driller and standardized penetrometer test (SPT) according to ASTM D1586 procedure. The project site was initially used as a municipal waste dumping area for more than 30 years. Hence, the top layers were mainly waste material and had to be removed upto 15 m to 20 m prior to geotechnical testing.

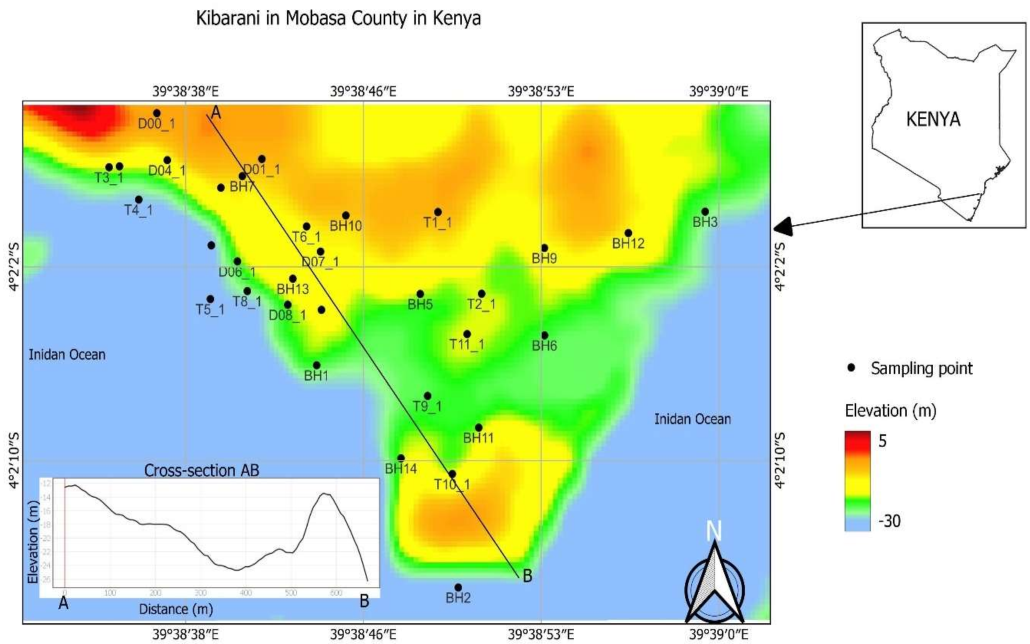

Figure 2: Construction project site

4.5. Data collection

Geotechnical investigations were carried out by drilling georeferenced boreholes (Figure 1) and carrying out in-situ testing (Standard Penetrometer Test (SPT) and vane shear test) and sampling for laboratory analysis of Atterberg limits (liquid and plastic limits). The tests and sampling were carried out on soil material at irregular depth intervals up to the rock restriction. SPT was carried out according to ASTM D1586/D1586M-18e1 and vane shear test according to ASTM D2573-08 standards. Samples for laboratory analyses were collected using the split barrel on the SPT equipment (Hunt, 2007). Liquid limit (LL) and plastic limit (PL) tests were done according to ASTM D4318. SPT test produced number of blows (SPT-N) to push the rod to penetrate 15 cm into the soil, vane shear test produced undrained shear resistance in kN/m^2, and Atterberg limits test produced liquid and plastic limits (Table 4).

Table 4: Range of values of soil properties from geotechnical site investigation

No.	Depth (m)	SPT-N (blows)	Resistance (kN/m^2)	Liquid limit (LL) (%)	Plastic limit (PL) (%)
1	1 - 11	3 - 30	33 - 101	22 - 48	13.6 - 34.7
2	2.5 - 13.6	5 - 32	38 - 121	27 - 64.2	12 - 33.9
3	4.5 - 22	5 - 32	38 - 133	27 - 50	12 - 33.9
4	10 - 28	15 - 37	45 - 189	25 - 44	13 - 30

SPT counts in boreholes were recorded at 1, 2, 5, 10, 15, 20, 25, and 30 m below the surface. These depth intervals were standardized to ensure uniform intervals for all boreholes in the project site. The tests were used to develop 3D model and show model's importance in risk assessment, visualization, and determination of presence of groundwater which may impact foundation design. 3D model was developed using a computer script written in R (R Core team, 2023). Risk assessment targeted presence of weak layers (low SPT Counts) within the subsurface. They are expected to cause uneven settlement that can cause foundation failure. Visualization targeted stratigraphic orientation of the subsurface to identify suitable areas that can be used to support different foundation designs.

The 3D model showed that shoreline areas had rather weak soil/rock material that may not support high stress foundation (Figure 3). The central parts of the site also seem to portray weak subsurface strata and fractured rocks. Borehole logs around these areas showed groundwater presence between 19m and 23 m below the surface. The northern parts and southern tip undulating into the Indian Ocean seem to have relatively deep soil with strong strata. There was no groundwater presence in these parts. Analysis of uncertainty showed that the areas with high SPT counts had relatively higher uncertainties than those with low SPT counts (Figure 4). This implies that even though the northern and southern parts of the project site are relatively strong, there may be local weak points that should be looked for during the design or construction. On the other hand, the central areas have high probability of bearing weak strata and should be targeted for low stress foundation applications. Uncertainty analysis in Figure 4 also shows that the top strata were more varied than the bottom strata.

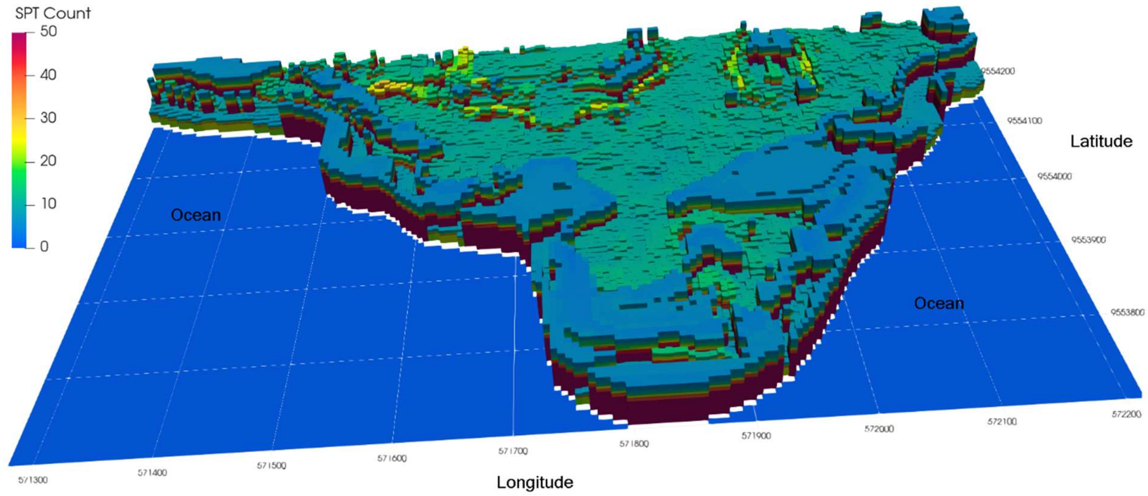

Figure 3: 3D model of relative subsurface strength of project site

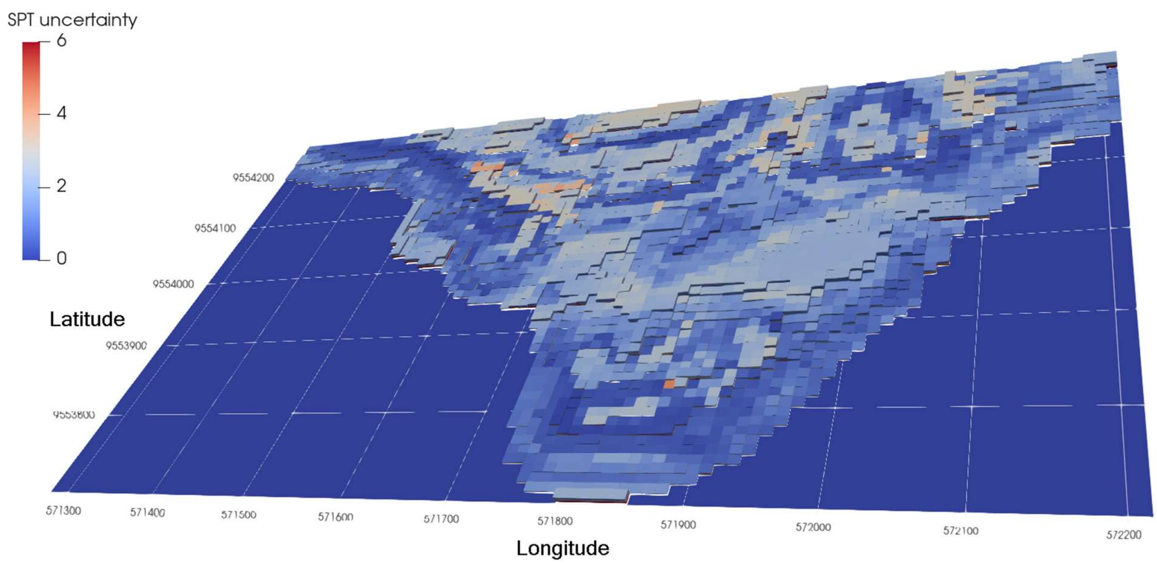

Figure 4: Prediction width at 95% confidence interval for 3D SPT count

5. Conclusions

3D model representation is very important in enhancing geotechnical investigations and improving site characterization. It has been widely used in geologic investigations but not so popular with geotechnical investigations. This study reviewed progress of 3D modelling in geotechnical investigations including current practices and opportunities for improvement. It showed that there has been an increasing demand for 3D representation of geotechnical investigations, which pushed the growth in adoption of 3D modelling techniques. The new techniques also complement the traditional investigation techniques. An indication of the growth in 3D modelling in geotechnical engineering is seen in the number of dedicated software that have since been developed. However, most dedicated software lack some important functionalities such as uncertainty assessment. Recent use of computer scripts as add-on to main software have seen improved versatility in incorporating uncertainty assessment in 3D models. They have a huge potential in opening up wide application of 3D modelling in geotechnical engineering.

Three broad application areas for 3D modelling in geotechnical investigations are subsurface risk assessment, 3D visualization, and identification of important subsurface sections/points. A case study application of 3D modelling was shown to summarize on-going activities in the literature.

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Statements and Declarations

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Data availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

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