Mohamad El Sibaii

Towrds efficient BIM use of underground geotechnical data

UMinho | 2020

University of Minho
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Master's dissertation
International Master in Sustainable Built Environment

Work Supervised by
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july 2020

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Acknowledgments

It is with great gratitude I thank my supervisor Prof. Miguel Azenha for the support and help given during the development of this dissertation and for believing in my idea and helping me execute it within my best potential. I would also like to thank Mr. Luís Bidarra for his support in technical issues encountered. My appreciation goes to each professor that has accompanied me during this Master's program and helped increase my knowledge and broaden my horizon through different challenges and great knowledge sharing.

I want to give my regards to all my colleagues who accompanied me on this journey and worked with me in many challenges. For each one of them who helped me pass through this Masters with joy and great companionship, I hope that our paths cross often in the future, as I think of you as close friends now.

My greatest appreciation goes heartedly to my wife Cátia Marques, my backbone. For pushing me to be the best version of myself through her unwavering consistent love and support. Pushing me to my limits to achieve the best results I can give. Believing in me and my capabilities. I thank her for the patience, time, and effort given to help me complete this dissertation as best as I possibly can.

To my family in Lebanon. Even though I am far from you, your love and support did not stop, you are everything that keeps me going. I give my greatest gratitude to God for the family I am blessed with. To my parents, whose care and love have crossed continents. To my mother, you are my inspiration to be caring, positive, and patient. To my father, you are my model in hard work and commitment. To my sister Rayan, you are my icon for creativity. To my sister Hiba, you are my icon for proactivity. To my brother Bilal, you are my icon for devotion.

To my wife's family in Portugal, whom I consider my own family. I want to express my deep appreciation for your love and support, you have been my family in this country and received me with open arms since the day I set foot in Portugal.

Most important of all, I express my gratitude to God for giving me the strength to fight for my goals. For having a plan for my life better than any plan I could have ever dreamed of.

الحمد لله دائماً و أبداً

Statement of integrity

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Resumo

A indústria de Arquitetura, Engenharia e Construção (AEC) tem mais recentemente abandonado o uso de métodos tradicionais e optado por se focar em processos colaborativos baseados no Building Information Modelling (BIM), o que por sua vez, tem trazido um conjunto de benefícios à construção. Destes benefícios destaca-se a maior sustentabilidade, com menos riscos, melhor gestão e o melhor desempenho nas construções. A mudança para o BIM teve origem no contexto de edifícios, alargando-se posteriormente também ao setor de infraestruturas. Neste estudo, procurou-se fazer uso de tecnologias de programação em BIM e metodologias de partilha de dados, no sentido de melhorar a forma como os dados geotécnicos podem ser usados e preservados. Será dada especial atenção à definição adequada de 'Product Data Templates' (PDT) específicos. As propostas a apresentar compreenderão cuidados específicos relativamente à interoperabilidade IFC. Especificamente, este estudo tem como objetivo propor uma metodologia para uso das informações extraídas de sondagens e relatórios geotécnicos em contexto BIM. Nesse contexto, propõe-se um PDT como padrão para armazenamento de dados de sondagens. A metodologia inclui um programa especificamente desenvolvido em plataforma BIM que utilizará dados coerentes com o PDT no sentido de gerar uma representação visual de sondagens e de camadas subterrâneas, anexando automaticamente dados das sondagens modeladas.

Palavras-chave: BIM, programação visual, engenharia Geotécnica, sondagens, *Product Data Template*.

Abstract

The Architecture, Engineering, and Construction (AEC) industry has, recently, abandoned the use of traditional methods and chose to focus on collaborative processes based on Building Information Modeling (BIM) that in turn brought many benefits to construction. Within these benefits, greater sustainability can be highlighted, with fewer risks, better management, and better performance in constructions. The move to BIM started in the context of buildings, subsequently extending to the infrastructure sector as well. In this study, it was intended to make use of BIM programming technologies and data sharing methodologies, to improve the way geotechnical data is used and preserved. Particular attention will be paid to the appropriate definition of specific 'Product Data Templates' (PDT). Proposals to be submitted will also comprise specific precautions concerning Industry Foundation Class (IFC) interoperability. Specifically, this study aims to propose a methodology for using information extracted from surveys and geotechnical reports in a BIM context. In this context, a PDT is proposed as a standard for storing survey data. The methodology includes a program specifically developed on a BIM platform that will use data consistent with the PDT to generate a visual representation of boreholes and underground layers, automatically attaching data to the modeled boreholes.

Keywords: BIM, Visual programing, Geotechnical engineering, Boreholes, Product Data Template.

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1 INTRODUCTION

1.1 Motivation

The construction industry has evolved a great deal in the past couple of centuries, it transferred from manual drafting to Computer-Aided Drafting (CAD) and finally to 3D modelling and BIM (Bradley, Li, Lark, & Dunn, 2016). Until very recently, the marked developments felt in the BIM context have been limited to the context of building construction, with few comprehensive developments in terms of design and construction of infrastructure. The benefits of implementing BIM in infrastructure are, however, booming (Kim & Gultekin-Bicer, 2018).

Currently, resorting to BIM methodologies is already a relatively widespread practice in several countries around the world, with some of these countries already making the use of BIM mandatory in various contexts (e.g. United Kingdom, France, and Spain). There are also several published regulatory provisions, which are, however, mostly intended for the design, construction, and maintenance of buildings, with no specific focus on infrastructure works (Bradley et al. 2016). However, in the last few years, several concrete developments can be witnessed in the bibliography for the context of infrastructure. Research in this area seems to be receiving considerably more attention today, highlighting the diverse benefits of implementing BIM in infrastructure (Morin, Hassall & Chandler, 2014).

The geotechnical information related to underground conditions is one of the most important factors at the beginning stages of a project that has big impacts on cost and schedule because of the non-uniform nature of the underground (Zhang, et al., 2018). The uncertainty of underground conditions and unidentified structures or utilities possesses a high potential for risk on construction projects (Tawelian & Mickovski, 2016).

The application of BIM technologies in geotechnical engineering can be a key solution in reducing any underlying risks. Many efforts have been made in the CAD and GIS platforms for the better use of information, but have not proven to be of high efficiency in improving the geotechnical investigation process. However, some attempts to find better workflows for the information management of infrastructural works have been fruitful and support this path of work (Zhang, Wu, Wang, Mao, & Wu, 2016, Tegtmeier, et al., 2014, Kim, Gultekin-Bicer, 2018).

When applying the BIM methodology, it is important to take into consideration that with the existence of multiple platforms for modelling and data processing, the information to be used must be transferable to an international format that allows its transfer to multiple platforms. An example of a highly used format for the interoperability of data is the Industry Foundation Classes (IFC) (Ma & Ren, 2017). This is a matter of great importance in order to standardize the process of preserving information, facilitate the sharing of information, and avoid the repetition and misuse or lack of use of information. Product Data Templates (PDT) are the latest innovation in the path of standardizing data in the construction industry (CIBSE, 2017).

Moreover, BIM platforms are encouraging innovation and the interaction of users with their platforms by using visual scripting programs. This technology is being utilized for finding solutions for problems in the construction industry as well as in the infrastructure sector.

1.2 Objectives

The overall aim of this work is to attempt to add an improvement on the way the BIM industry currently interacts with geotechnical data by: (i) proposing a uniformized process of archiving geotechnical data, (ii) develope a program that uses the geotechnical data from geotechnical reports to make it available in a BIM context, and (iii) to validate the work on a case study.

(i) Regarding the uniformization of the process of archiving geotechnical data, the main objective is to create a unified digital form for the stakeholders involved in producing geotechnical data. A review is made on Product Data Templates, and a proposal of one related to geotechnical data is made. A methodology is presented with focus on how its elements have been selected, taking into consideration that the PDT would be a unified form used by multiple stakeholders.

(ii) In regards to the developement of a program that uses the geotechnical data from geotechnical reports to make it available in a BIM context. The main goal was to create a program using a visual scripting tool that would facilitate the transfer of data from geotechnical reports to a visual representation of the elements in a BIM platform. This process is to be made taking into consideration the importance of preserving geotechnical data associated with the elements and ensuring the interoperability of all the elements created for the sake of sharing these data and for future use.

(iii) To validate the work, a case study for a real project was performed. The main goal of this step was to see the result of using the PDT and the fore mentioned program on real data. Then it was necessary to analyze the outcome of the work in the context of the real project and the work developed in this dissertation.

1.3 Dissertation Outline

This dissertation is organized into six parts, where the first one consists of this introduction. It includes the motivation of the work, objectives with a hint on methodology, and lastly this dissertation outline.

In the second part presents the literature review about the different subjects addressed in this dissertation. It initially addresses the issue of BIM in infrastructure, where a brief introduction to BIM and where it stands concerning infrastructure is presented. Then the matter of object definition in BIM and PDTs is discussed, and finally, visual programming and interoperability issues in BIM contexts are addressed. A review is also made on the scope of geotechnical engineering and specifically geotechnical investigation reports, with explanation of the traditional and the BIM approach to handling the data derived from these reports. Finally, the current BIM tools in geotechnical engineering are discussed.

Part three of this dissertation focuses on the proposal of a Product Data Template specifically for boreholes, which has its data derived from the geotechnical investigation reports. A discussion about how the selection of the parameters that constitute the PDT was performed, and a custom PDT is proposed.

In part four, the matter of visual programming is addressed as a tool to create a program that would enhance the way geotechnical data is handled after the initial geotechnical investigation report is produced. This is achieved by directing the data through the use of PDTs and visual programming to be presented visually in a BIM platform and an interoperable format.

Part five holds the case study that has been chosen to be performed using real data, as a means to validate the work, show the results of the program created and analyzing the outcome. It also addresses the challenges that were faced in performing the case study, and what benefits were seen in the context of the project analyzed.

Finally, part six provides a summary of the conclusions made and lessons learned. It also has possible suggestions for future studies that can improve and develop this work.

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2 DATA MANAGEMENT IN GEOTECHNICAL ENGINEERING: TRADITIONAL AND NEW APPROACHES

This part of the work is a review of the state of the art on BIM and its development and its relation to infrastructure and BIM's relation with geotechnical engineering. The first section includes a revision of BIM itself and its development, PDT and object normalization, visual programming, interoperability, and the move of BIM to infrastructure. The second section takes on the subject of data flow in geotechnical engineering with a definition of geotechnical investigations and their traditional and BIM approaches and the current BIM tools in geotechnical engineering.

2.1 BIM in infrastructure

2.1.1 BIM definition and current development

2.1.1.1 BIM definition

Building Information Modelling is one of the most promising processes under development in the AECO industry. It is the process of simulation of a construction project in a virtual environment. At the end of the modelling process, an accurate virtual model of a structure is digitally constructed and it contains precise geometry and relevant data that is important for the support of the real-life construction, fabrication, and procurement activities (Eastman, Teicholz, Sacks, & Liston, 2008). This paradigm shift of digitalization in the building sector requires some adaptation to make full use of the benefits of the process.

The process of generation of documentation for the construction industry has passed through different stages in the past decades as the construction projects became more complex and required better virtual representations, communication between stakeholders, information sharing, and collaboration. It has also been used to decrease project costs, increase productivity and quality, and reducing project delivery time (Azhar, Nadeem, Mok & Leung, 2008).

The main stages of this process are divided into three stages: the manual stage, the digital stage and the BIM stage (Pérez-Sánchez, Mora-García, Pérez-Sánchez, & Piedecausa-García, 2017) (see fig. 1). The manual stage is the classic method of drafting using pen, ruler and other tools; the CAD phase is the computerized stage where drafts started to be made digitally; the BIM phase is when the digital objects started to represent the real objects including specific features and information that lies behind the image.

Figure 1: Left: Manual drafting table (Emmeitalia). Middle: Sketchpad (Sutherland, 1964). Right: BIM software (Tekla)

BIM was conceived primarily for improving design and construction, but rapidly the benefits of BIM stretched its arms to include all other stages of the lifecycle of projects. It is currently a process for managing information throughout the whole lifecycle of a project including operation and management of the asset and even demolition.

The main benefit of BIM lies in the tools which allow collaborative work between all the parties of the AECO industry, which results in more work efficiency. The creation of a digital information model where all parts of the AECO industry have contributed to add essential information throughout the project on every element in the model and digitize the information which otherwise would have been hard to find or access would result in a greater whole life value for the asset (WSP, 2017).

The information that is integrated into the BIM platform has improved and increased the quality of digital representations of the real elements in the platform. This information is usually represented in the BIM platform as objects that are geometrical entities present in the platform in specific locations and that are composed of graphical and non-graphical information that describe the real element. The graphical data gives the object its recognizable shape and the non-graphical data allows the object to behave in the same way as the real product (NBS, 2017). Taking an example of a column as a BIM object, it can be said that the type of the element is “column” and the information related to this element would be about material properties (structural material, density, compressive strength … etc.), sectional properties (height, width … etc.), and purpose of the element (the type of connection with other elements) (see fig. 2).

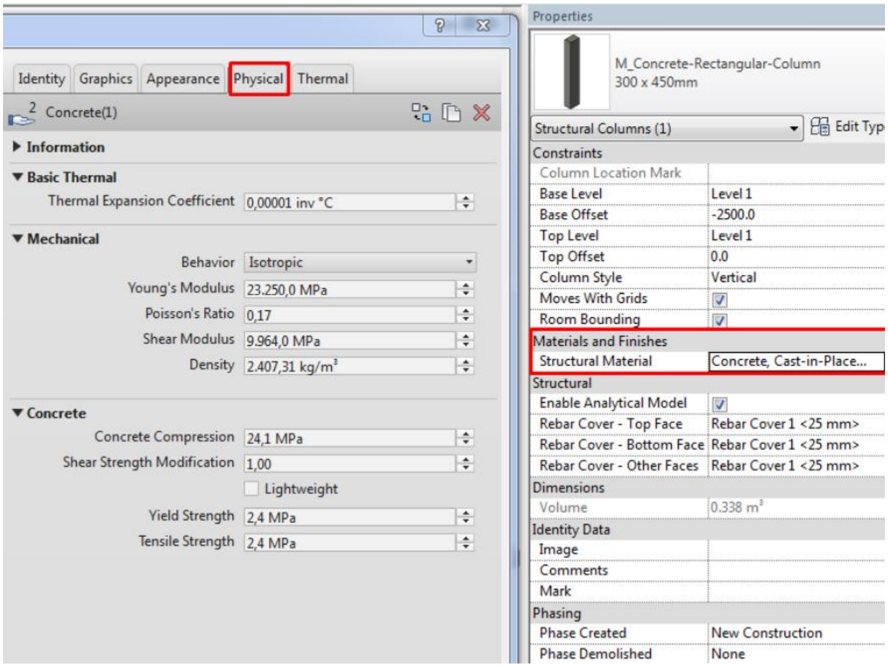


Figure 2: Column Properties in Revit (Fernandez, 2019)

2.1.1.2 BIM dimensions

The evolution of the kind of information that can be linked to the 3D model in the AECO industry is defined by dimensions, and hence with more information of different types to be linked to the model, it evolves in its dimensions (see fig. 3)

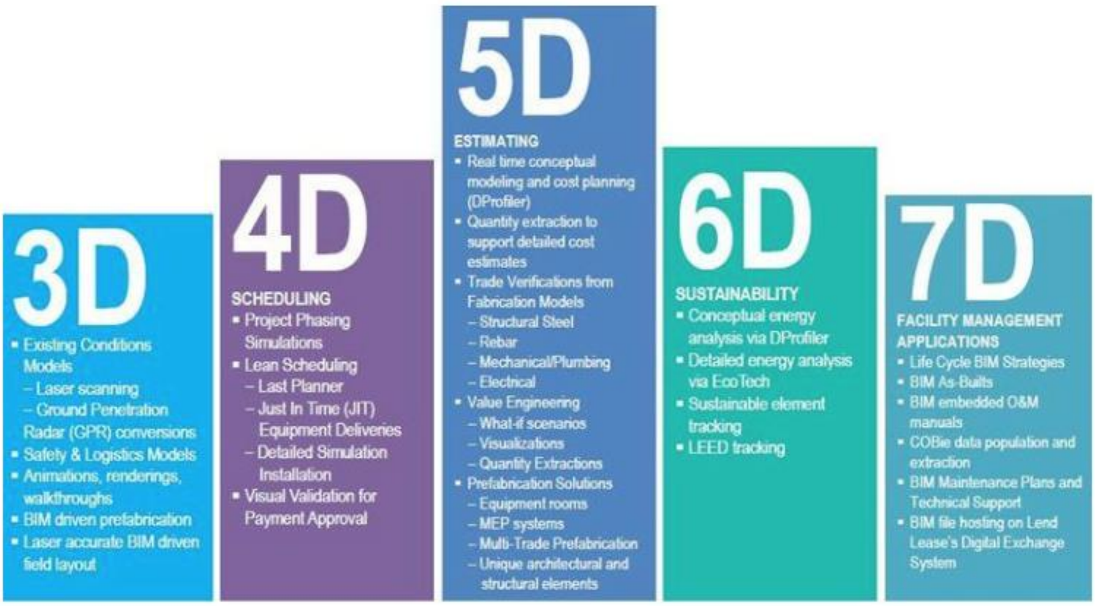


Figure 3: BIM dimensions (McPartland 2017)

The dimensions can be simplified as follows:

- 3D: (Geometry) The process of creating graphical and non-graphical information and sharing it in a common data environment.
- 4D: (Time) The scheduling data of a project is incorporated into the model and hence it is correlated with the time dimension.
- 5D: (Money) The inclusion of information related to the costs of the elements of the model.
- 6D: (Sustainability) The shift to analyzing the energy consumption and lifecycle related costs of a project.
- 7D: (Facility Management) Tracking important asset data such as its status, maintenance/operation manuals, warranty information, technical specifications, etc. to be used at a future stage.

2.1.1.3 BIM levels

The level of maturity or BIM level of the model defines the criteria that are required for a model to be BIM-compliant. The BIM level increases from zero to three with the increase of the level of collaboration and exchange of information set by the project (NBS, 2014) (see fig. 4).

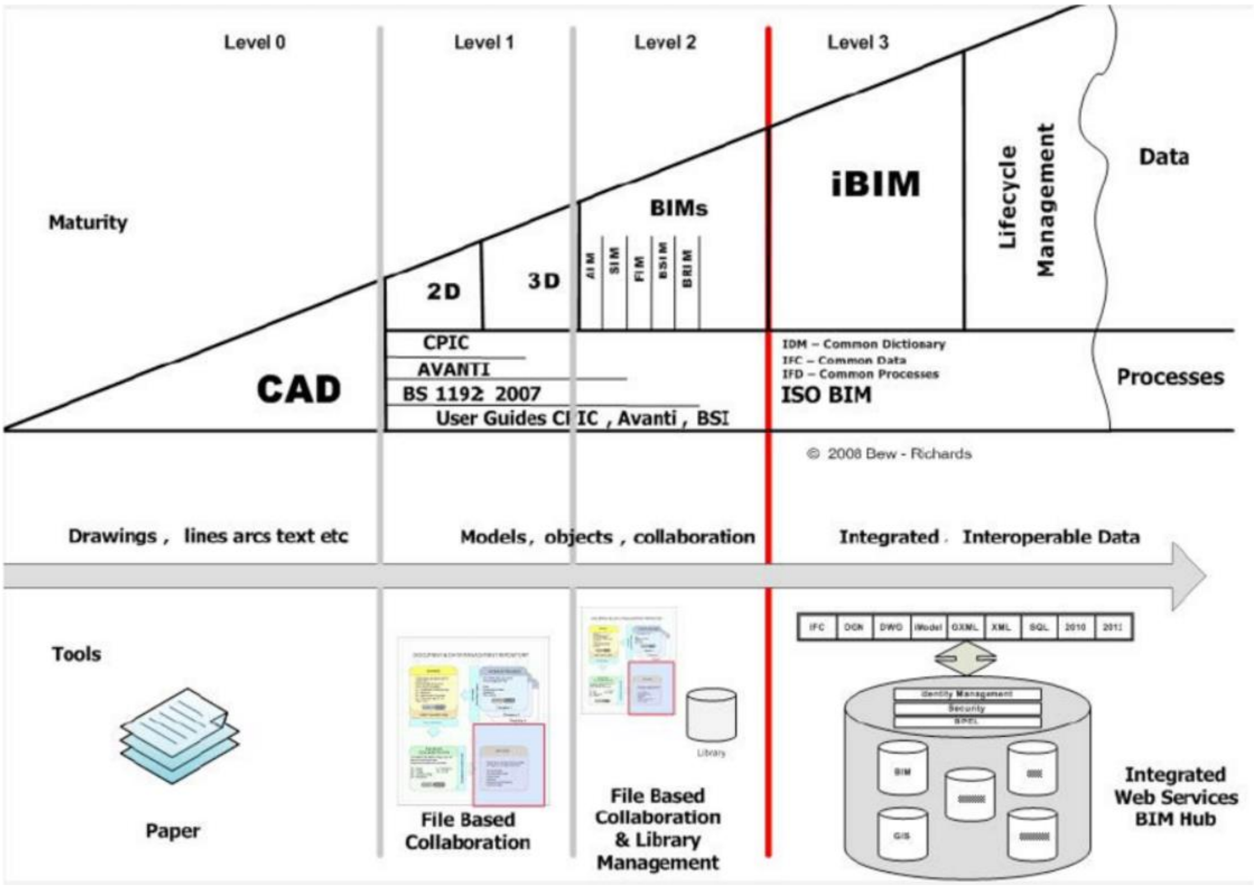


Figure 4: BIM Maturity Diagram (Bew & Richards, 2008)

This system of levels was developed in the UK for its progressive movement of the construction industry into a fully collaborative process. The levels can be summarized as follows:

Level 0: means no collaboration and output of material is via paper or electronic prints or both. Most of the industry is ahead of this phase.

Level 1: is where there is sharing of information through a common data environment

Level 2: is where the sharing of information is through federated BIM models. A federated BIM model is when several different models are compiled by amalgamating into one model, or by importing one model into another (NBS, 2017).

Level 3: is for the full collaboration between different disciplines using one single shared model (Waterhouse & Philp, 2017).

2.1.1.4 Standardization of BIM processes

Countries around the world are in the direction of adopting BIM for construction works, with most countries taking a bottom-up approach with BIM adoption, some countries are taking a top-down approach by mandating the use of BIM (see fig. 5). The UK is one of the countries leading this movement, and they have produced a suite of documents that give the industry the tools, processes, and procedures to work at a BIM level, and their work on data sharing guides have made their impact on a global scale.

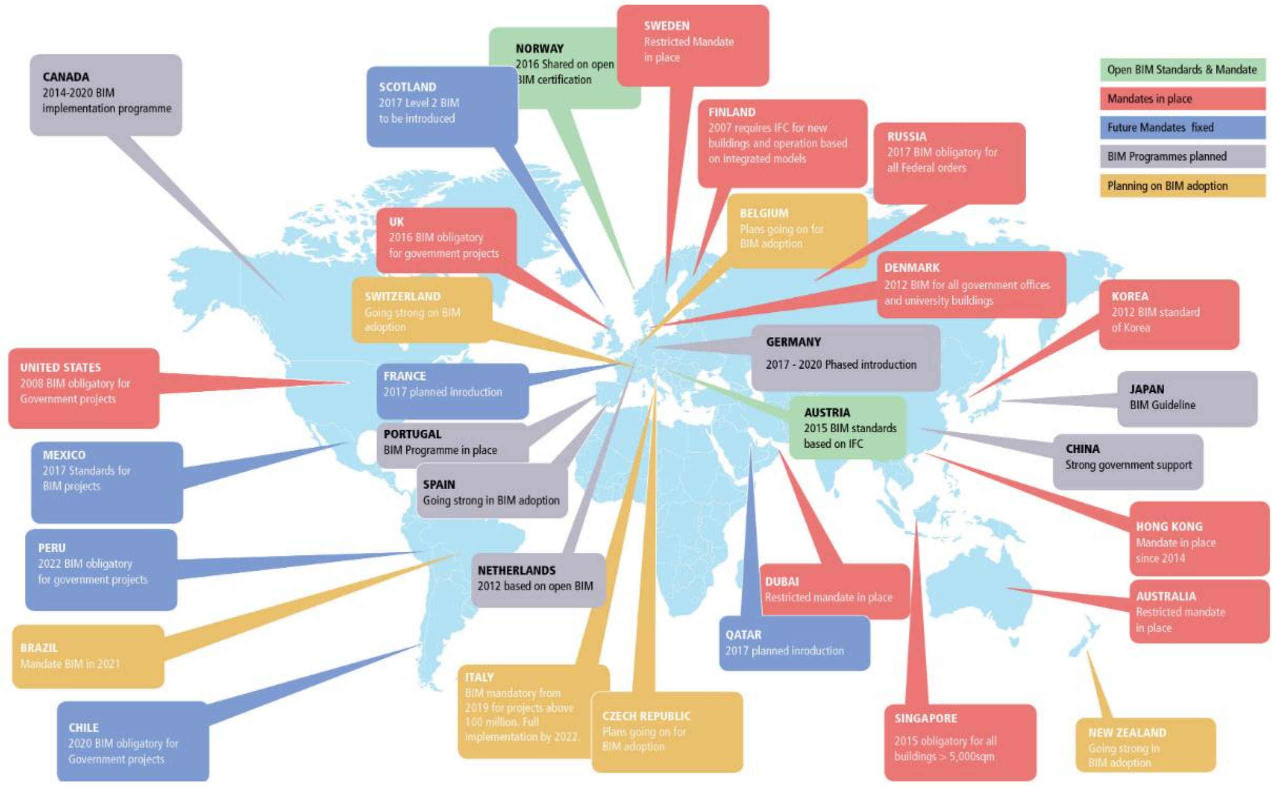


Figure 5: Map of global BIM evolution (Shimonti, 2018)

The well-structured creation and exchange of information is what characterizes BIM. "Better Information Management" is a term that has been referred to for this process. Because of the high amounts of stakeholders and contributors to the process of BIM, which can result in different and contradicting views and interests and produces large amounts of uncertainties and questions around the flow of information in a project (see fig. 6), a key factor for the success of this process is the organization of information in the context of project management and ensuring high-quality production and use of information. In this context, standardized processes and definitions would help to ensure that information be put to the best use and reuse most efficiently without change or interpretation (Scheffer, Mattern, & Konig, 2018).

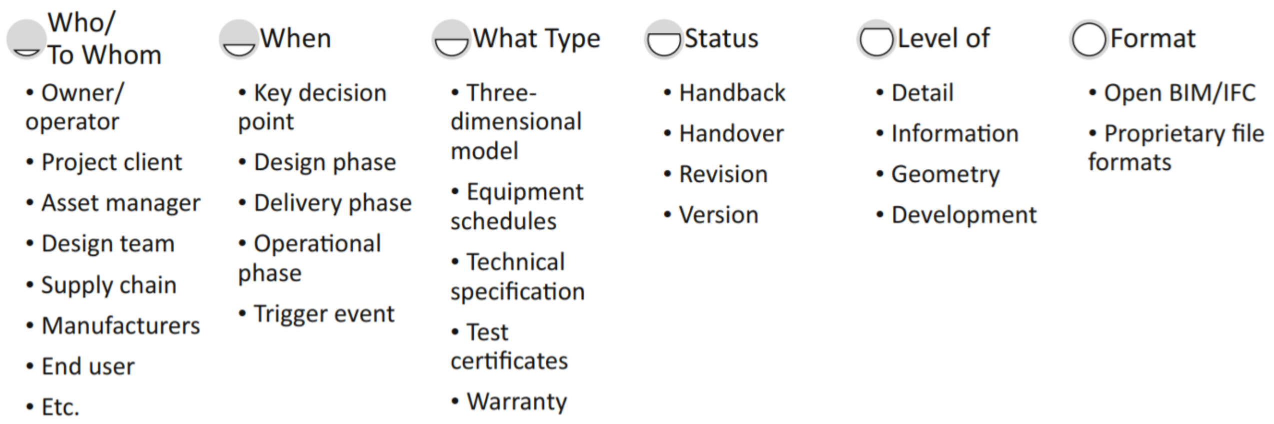


Figure 6: Questions related to the project information flow (Scheffer, et al., 2018)

The standardization of BIM processes is a key factor in realizing efficient BIM project management. One of the most important sets of standards developed in this context is the British Standard of the International Organization for Standardization (ISO) ISO 19650 (ISO 19650-1, 2018), which is published by the European Committee for Standardization (CEN) (CEN/TC 442, 2018). It has become a very influential set of standards, and many projects have been conducted worldwide implementing its principles. This document frameworks the concepts and principles for information management at a stage of maturity described as "building information modelling (BIM) according to the ISO 19650 series". It is used in the whole life cycle of any built asset and can be adapted to projects of any scale and complexity. These standards ensure that the necessary information, with its purpose and required content, is delivered for the sake of the BIM execution plan and the information requirements of the employer. It also elaborates on the reliable information, based on the Level Of Model Definition (LOMD) which is elaborated in the next section, that should be delivered to the client at key decision points “data drops” (see fig.8), that signifies for information exchange between employer and employee at certain milestones in the schedule of a project, to ensure that the full benefit of this process is reached in the long-term perspective (Lee, & Borrmann, 2020).

2.1.2 Objects in BIM and Product Data Templates

2.1.2.1 Object definition and standardization

By enabling BIM methodology, an asset can be represented virtually by a set of objects that carry detailed information about how they are constructed and also capture the relationship with other objects in the asset model. A BIM object is a combination of the detailed information that defines the product and its geometry. The visualization data that defines the object’s appearance and behavior enable the object to be positioned or to behave in the same manner as the real product. It is vital to understand that to ensure that the virtual environment is accurately representing the real world, the way a product works must be fully understood. And to do that, the type of information that would be found in this product's data sheet and relevant technical details must be combined with information on dimensions and functionality so that the product is effectively represented for the stakeholders who would use it in a BIM project (see fig. 7). To better improve the object, it is also advised the addition of relevant specifications and interoperability properties associated with the project. Products of the same type would have the same data sets consistency which would allow designers to compare BIM objects accurately and efficiently. (NBS, 2017)

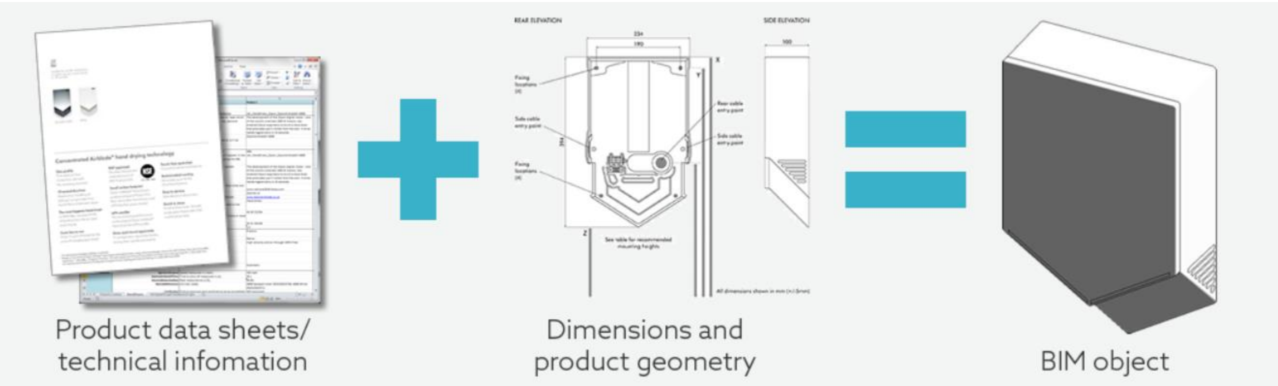


Figure 7: Constituents of a BIM object (NBS, 2017)

There are two main types of objects: 'component' and 'layered'. The component objects are building products that have fixed geometrical shapes such as windows, doors, boilers, etc., and the layered objects are building products that do not have a fixed shape or size such as carpets, roofing, walls, and ceilings (NBS, 2017).

Objects may also be said to be 'generic' or 'specific', where generic objects, often called library objects, are used during the initial design phase as placeholders as a visual expression of the need for a specific object to be selected at a later stage, and specific objects, often called manufacturer objects, are those objects that represent a manufacturer's specific products (NBS, 2017).

As mentioned earlier, objects commonly have data sheets or specifications attached to them. The amount of information present in these data sheets and specifications is defined by a level of detail (Lod) and a level of information (LoI), where the level of detail defines the accuracy of the geometric virtual representation of an object, and the level of information defines the level of details of information embedded in that virtual object (designingbuildings, 2019).

The Level Of Model Definition is a combination of graphical “Lod”, and non-graphical “LoI”, and it is a main factor in dictating an object’s geometrical details and amount of information attached to it depending on the phase it is presented in a project (designingbuildings, 2019).

The LOMD is broadly defined in the British Standard (BS) PAS 1192-2 (BSI, 2013), now replaced by BS ISO 19650, and it is divided according to the stage of the project in the construction schedule (see fig. 8 & 9).

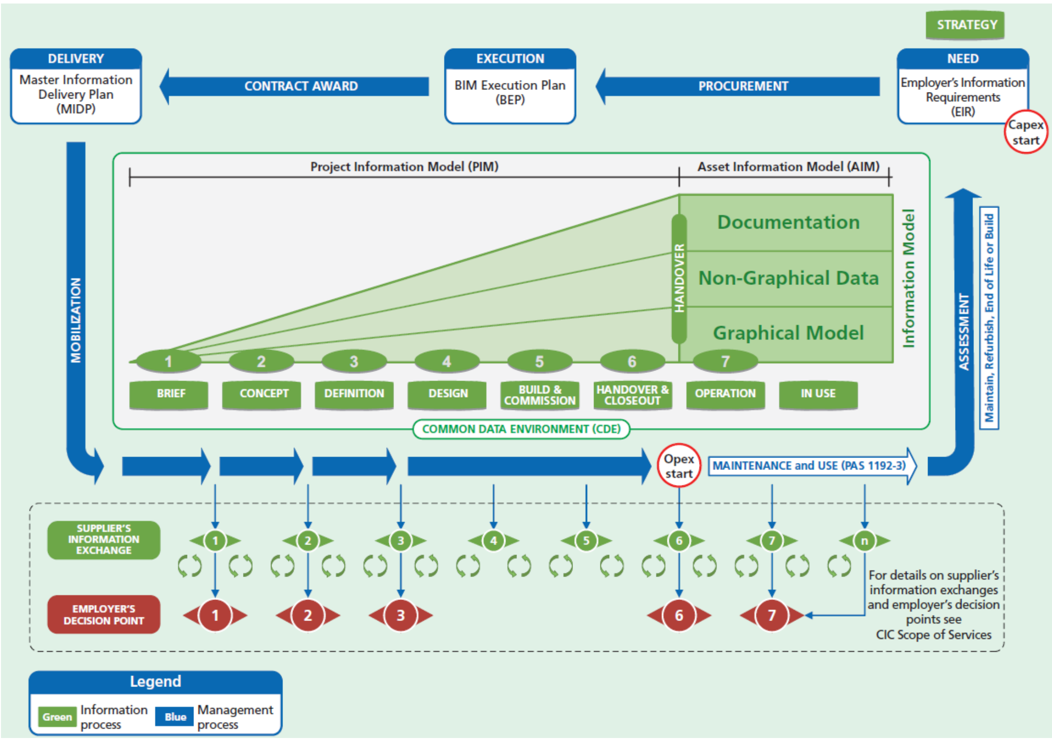
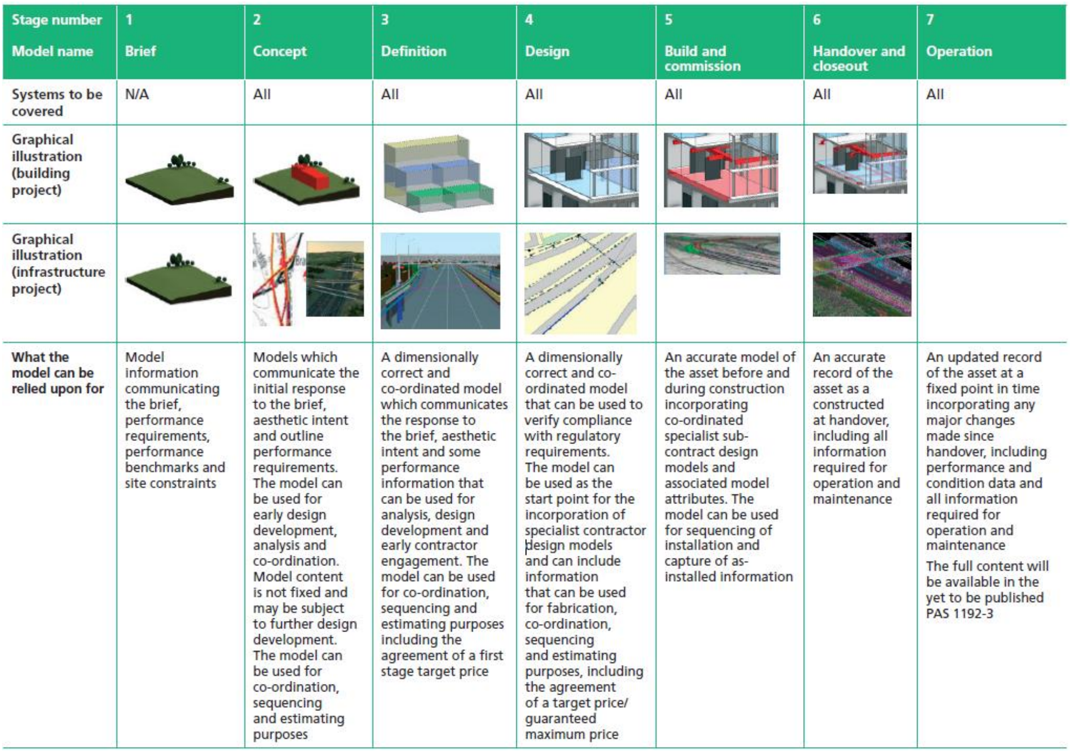


Figure 8: The information delivery cycle (BSI, 2013)

Each stage defines the set of information that should be available and shared between stakeholders of a project on data drops. The stages are defined as follows:

- Brief: If a graphical model exists it is most probably been developed from an existing asset information model. Information about existing structures might be related.
- Concept: The graphical design could have mass diagrams and 2D symbols to represent generic elements.
- Definition: Based on generic representations, and specifications and attributes on objects, the selection of products is allowed.
- Design: Information about space allocation for operation, access, maintenance, installation, and replacement are attached to objects represented in 3D.

- Build and commission: Manufacturer's objects replace generic objects, with information re-linked to the replacement objects with manufacturer information.
- Handover and close-out: The model represents the as-built project and all necessary data is included in the handover of documentation, including maintenance and operation documentation, commissioning records, health and safety requirements.
- Operation and in-use: Performance is verified as per the Employer's Information Requirements and the project brief. If changes are necessary, the model is updated. Information about maintenance, replacement dates, and so on can be attached.



Stage number Model name	1 Brief	2 Concept	3 Definition	4 Design	5 Build and commission	6 Handover and closeout	7 Operation
Systems to be covered	N/A	All	All	All	All	All	All
Graphical illustration (building project)							
Graphical illustration (infrastructure project)							
What the model can be relied upon for	Model information communicating the brief, performance requirements, performance benchmarks and site constraints	Models which communicate the initial response to the brief, aesthetic intent and outline performance requirements. The model can be used for early design development, analysis and co-ordination. Model content is not fixed and may be subject to further design development. The model can be used for co-ordination, sequencing and estimating purposes	A dimensionally correct and co-ordinated model which communicates the response to the brief, aesthetic intent and some performance information that can be used for analysis, design development and early contractor engagement. The model can be used for co-ordination, sequencing and estimating purposes including the agreement of a first stage target price	A dimensionally correct and co-ordinated model that can be used to verify compliance with regulatory requirements. The model can be used as the start point for the incorporation of specialist contractor design models and can include information that can be used for fabrication, co-ordination, sequencing and estimating purposes, including the agreement of a target price/ guaranteed maximum price	An accurate model of the asset before and during construction incorporating co-ordinated specialist sub-contract design models and associated model attributes. The model can be used for sequencing of installation and capture of as-installed information	An accurate record of the asset as a constructed at handover, including all information required for operation and maintenance	An updated record of the asset at a fixed point in time incorporating any major changes made since handover, including performance and condition data and all information required for operation and maintenance The full content will be available in the yet to be published PAS 1192-3

Figure 9: Part of levels of model definition for building and infrastructure project (BSI, 2013)

The LOMD is also referred to the Level of Development LOD in American standards and it has the same purpose but with different naming and structure (see fig: 10), where:

- LOD 100: The Model Element can be represented graphically in the Model with a symbol or a generic representation, but does not fulfill the requirements for LOD 200. Information related to the Model Element can be taken from other Model Elements.
- LOD 200: The Model Element is graphically represented in the Model as a generic system, object, or assembly with rough quantities, size, shape, location, and orientation. Non-graphic information can be attached to the Model Element.

- LOD 300: The Model Element is represented graphically within the Model as a specific system, object, or assembly in terms of size, quantity, location, shape, and orientation. Non-graphic information can be attached to the Model Element.
- LOD 350: The Model Element is represented graphically in the Model as a specific system, object, or assembly in terms of size, quantity, shape, and orientation, and connection with other building systems. Non-graphic information can be attached to the Model Element.
- LOD 400: The Model Element is represented graphically in the Model as a specific system, object, or assembly in terms of size, quantity, shape, location, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information can also be attached to the Model Element.
- LOD 500: The Model Element is an as-built verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information can be attached to the Model Elements.

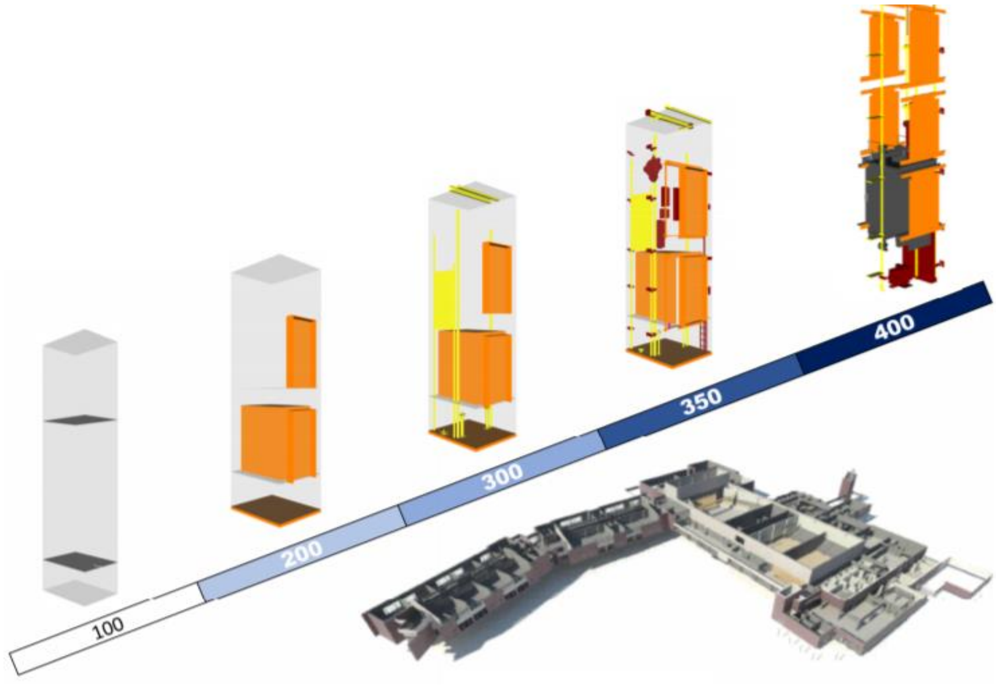


Figure 10: Levels of Development (BIMForum, 2019)

BIM objects can be made available in a range of file formats, suitable for use in different BIM software, and they can also be provided in an open exchange, platform-neutral formats, like IFC. This is important as projects will be worked on by designers using different platforms, and will be analyzed by contractors, quantity surveyors, and facilities managers also using different platforms, making interoperability of objects a very important aspect to reflect on. As mentioned earlier the standardization of processes is key in its success, and in that context, there have been many approaches in the construction industry for the standardization of BIM objects. NBS BIM Object Standard is one of the works which helped set a common approach to quality standards across the industry, encouraging consistency and collaboration. It defines the information, geometry, behavior, and presentation of BIM objects to maximize consistency, efficiency and interoperability across the construction industry (NBS, 2019)

2.1.2.2 Product Data Templates

The governmental demand for the standardization of information, to be provided in a structured and consistent form, has pushed several national and international activities for the creation of what could be the solution for manufacturers, contractors, and building operators to create a unified form of data preservation which includes all project and asset information, documentation and data in an electronic medium, a Product Data Template (PDT).

PDTs describe the data fields needed to define products. These data fields are sets of attributes and parameters that are presented in a standardized structured tabular format to accurately describe objects, allowing comparisons and better model creation. (Lucky, Pasini & Lupica, 2019). A PDT is expected to contain all the necessary information of a product that is believed to be useful for all users of this product from commissioning to its end of life.

As per the European directives and regulations, manufacturers are required to provide detailed and structured information about their products. Hence, if the information is structured in a consistent, detailed, and coherent databases, it will allow manufacturers to cope with their duty in accomplishing regulation and directives.

The European Committee for Standardization (CEN) with the International Organization for Standardization (ISO) currently have the standard ISO 23387 titled "*Building information modelling (BIM) - Data templates for construction objects used in the life cycle of any built asset - Concepts and principles*" (ISO/FDIS 23387, 2020) under the status "under approval" and it is yet to be published. This standard sets out the concepts, principles, and the general structure for product data templates for products used in construction works.

The Chartered Institution of Building Services Engineers (CIBSE) is one of the main institutes working in the creation of PDTs for the industry. It has an available master Product Data Template for users where it sets the standard format to be used by all users, which increases its efficiency in saving and transferring data between different stakeholders (see fig. 11) (CIBSE, 2017).

The Chartered Institution of Building Services Engineers
Product Data Template

Product Title

Template Category				
Template Version	▼			
Category Description	**Description**			
Classification System				
Classification	**Value**			
Suitability for Use				
Template Custodian	**CIBSE**			
Information Category	**Parameter Name**	**Value**	**Units**	**Notes**
Manufacturer Data				
Specifications	Manufacturer		Text	
Specifications	Manufacturer Website		URL	
Specifications	Product Range		Text	
Specifications	Product Model Number		Text	Or Code
Specifications	CE Approval		Text	Number, Yes, No
Specifications	Product Literature		URL	
Specifications	Features		Text	Free text to describe product
Construction Data				
Specifications	Type		Text	This is a COBie field, other fields will be required in final PDTs
Specifications	Shape		Text	This is a COBie field, other fields will be required in final PDTs
Specifications	Material		Text	This is a COBie field, other fields will be required in final PDTs
Specifications	Colour		Text	This is a COBie field, other fields will be required in final PDTs
Specifications	Finish		Text	This is a COBie field, other fields will be required in final PDTs
Application Data				
Specifications	Reference Standard		Text	
Specifications	Power Source (if required)		Text	e.g. Integral battery, System-powered, Other, UserDefined
Dimensional Data				
Specifications	Overall Length		mm	Or Diameter. Minimum and maximum lengths available
Specifications	Overall Width		mm	Minimum and maximum widths available
Specifications	Overall Height		mm	Minimum and maximum heights available
Specifications	Gross Weight		kg	Equates to Operating Weight
Specifications	Shipping Weight		kg	Equates to dry weight of unit plus packaging allowance
Specifications	Access Clearance Top		mm	Access required for maintenance of this item
Specifications	Access Clearance Bottom		mm	Access required for maintenance of this item
Specifications	Access Clearance Left		mm	Access required for maintenance of this item
Specifications	Access Clearance Right		mm	Access required for maintenance of this item
Specifications	Access Clearance Front		mm	Access required for maintenance of this item
Specifications	Access Clearance Rear		mm	Access required for maintenance of this item
Performance Data				
Specifications	Coverage Area		m^2	
Specifications	Set Point Concentration		ppm	
Electrical Data (if required)				
Specifications	Battery Supply		Y/N	
Specifications	Battery Type		Text	e.g. Alkaline, Lithium Ion Rechargeable
Specifications	Voltage		Volts	
Specifications	Supply Phase		Number	1,3
Specifications	Frequency		Hertz	eg. N/A, DC, 50, 60, Other, UserDefined
Specifications	Enclosure Rating		Text	IP rating
Specifications	Number of Poles		Number	e.g. N/A, 1, 3
Controls				
Specifications	Fire Control Panel Links		Y/N	
Specifications	BMS Links		Y/N	
Sustainability				
Sustainable Material	Embodied Carbon		kgCO2	University of Bath ICE Data if none other available
Sustainable Material	Life Cycle Analysis		Number	BREEAM
Sustainable Material	Location of Manufacturer		GridRef	Northing,Easting

Figure 11: Master Product Data Template form (CIBSE 2017)

The PDT structure from CIBSE consists of a header section and four main columns, which are the Information category, the parameter, the value, and the Guidance note. The header section has the Category metadata with Information about the PDT (Template category, template version, category description, classification system, etc.). The four columns hold the Category specifications which are divided into nine divisions:

The manufacturer data (manufacturer, manufacturer website, product range, product model number, etc.), construction data (type, shape, material, color, finish), application data (reference standard, the power source), dimensional data (overall length, overall width, overall height, etc.), performance data (coverage area, setpoint concentration), electrical Data (if required) (battery supply, battery type, voltage, etc.), and controls (fire control panel link, BMS links), sustainability (embodied carbon, life cycle analysis, the location of the manufacturer, a green guide for specification, etc.), operation and maintenance (operation and maintenance manual, daily, weekly, monthly, quarterly, etc.).

PDTs present a unique form of preserving data in a digital way, which is very helpful for engineers in cutting back on data entry in the BIM model, which normally was an extensive procedure, now is a much faster and easier nearly automated procedure, where all the information in PDT are in a BIM usable format. The benefits of PDT have been proven to be efficient in improving the communication of data in the building sector, particularly through the shared libraries like building SMARTdata dictionaries (bSDD, 2018) which are used to identify any object in the built environment with its properties, regardless of language which makes this an international platform that transcends language barriers and promotes worldwide sharing of information. However, the movement of PDT has not yet proven to be as efficient in fulfilling the needs of infrastructure life cycle assets (buildingSMART, 2018).

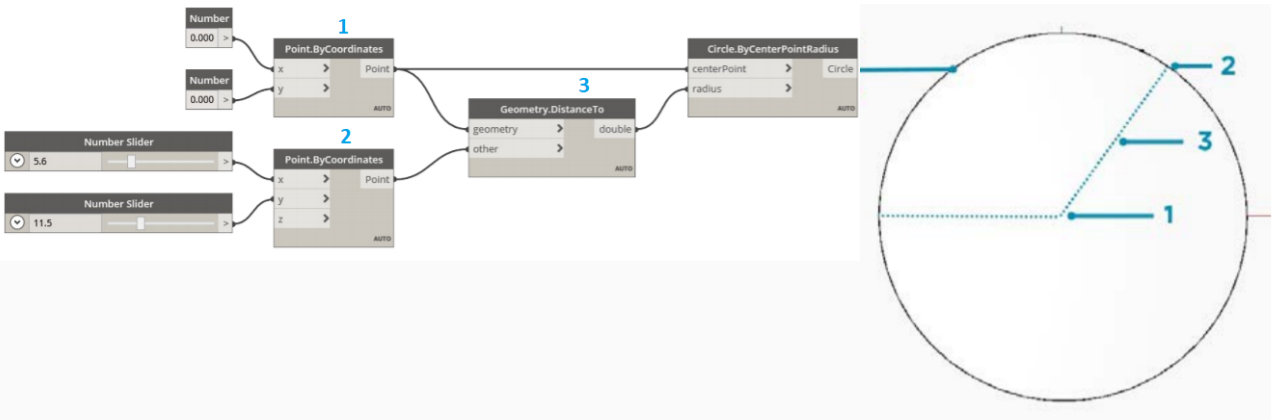
2.1.3 Visual Programming

2.1.3.1 History and definition

Visual programming languages (VPL) were developed in the seventies and arose from the collaboration of work in computer graphics, programming languages, and human-computer interaction fields (Boshernitsan, & Downes, 2014). A VPL is a language that allows the user to create their personalized programs or algorithms by manipulating program elements graphically rather than textually, which makes the human-computer interface friendlier which facilitates learning and using of programming language (Craftai, 2015).

To use textual programming users need to learn syntax language to be able to encode programs. However, in VPL programs are coded using graphical elements that are called nodes. These visual nodes have textual programming codes hidden inside of them, so when the user creates a program using these nodes, they are, indirectly producing programming codes.®

The process of creating geometry, for example, can be done in textual or visual programming, where both of these methods use the same framework. An example in figure 12 is shown to clarify the process of the creation of a simple circle in textual versus graphical methods. There are three basic nodes to define 2 points that define the radius and the center of a simple circle in the visual programming tool.




```
myPoint = Point.ByCoordinates(0.0,0.0,0.0);
x = 5.6;
y = 11.5;
attractorPoint = Point.ByCoordinates(x,y,0.0);
dist = myPoint.DistanceTo(attractorPoint);
myCircle = Circle.ByCenterPointRadius(myPoint,dist);
```

Figure 12: An example to draw a simple circle in graphical (top) and textual (bottom) programming (Fernandes, Azenha, & Couto, 2015)

This method of programming is mainly used for the creation of geometry using parametric modelling. In 1988 Parametric modelling methodology became popular with the creation of the first commercially successful parametric software in BIM history, when Parametric Technology Corporation released Pro/ENGINEER. In 2000 Revit was developed by Charles River Software, it revolutionized BIM by using a parametric change engine made possible through object-oriented programming, and by creating a platform that allowed time attribute to be added (Cherkaoui H., 2017).

VPL is mainly used for, among other things, the generation of geometry through parametric modelling. The methodology of parametric modelling enables designers to explore multiple designs easier and without causing extra costs for making design changes (Teresko, 1993). By using parametric modelling, any complex geometry can be created by the user, and the influence of modifying any set parameter can be seen easily. This process makes it more intuitive to perform changes on parameters of a final model to see the desired result of these changes.

A visual programming tool is a powerful tool for creative and innovative problem-solving in the BIM platform. Endless innovative works have been made in the scripting programming language, tasks that required enormous amounts of work have been simplified and the work automated using its tools, which saved time and money for its users (Fernandes, Azenha, & Couto, 2015, Monteiro, 2016, Torbjorn, 2017).

2.1.3.2 VPL tools

In the last recent years, many building design software has adapted VPL as a part of their products. This interesting strategy of combining VPL and BIM models authoring tools have been exploited by the users of BIM software on many levels as the applications primarily focused on 3D parametric modelling and in studies of complex architecture(Stavric, & Marina, 2011), it rapidly extended its functionalities into different subjects (Preidel, & Bormann, 2016)(Kensek, 2015). Some of these tools that are leading the market are Dynamo, which is integrated with Autodesk Revit, Generative Components, which is integrated with Bentley AECOsim, and Grasshopper, which is integrated with Rhinoceros.

Dynamo, Autodesk’s extension for Revit, is an open-source tool that is one of the leading visual programming tool implemented in BIM software. This tool although mainly a visual programming tool also possesses the capability of accepting textual programming language. It is made to be accessible to programmers and non-programmers alike. It enables the user to work in a visual process to connect different nodes to form the desired algorithm for whatever purpose intended, whether creating geometry or processing data. Endless innovative works have been made in this scripting programming language, tasks that required enormous amounts of work have been simplified and the work automated using this tool, which saved time and money for its users (Torbjorn, 2017).

Generative Components, developed by Bentley, is a parametric software where users can interact with the platform by dynamically modelling and directly manipulating geometry, applying rules and capturing relationships among model elements, or by defining complex forms and systems through concisely expressed algorithms. It is an associative and parametric modelling system used by architects and engineers to automate design processes and accelerate design iterations. It gives designers and engineers new ways to efficiently explore alternative building forms without manually building the detailed design model for each scenario. It also increases their efficiency in managing conventional design and documentation (Bentley, 2020).

Grasshopper, a plugin for the Rhinoceros 3D, is a graphical algorithm editor that offers new ways to explore the 3D design and modelling processes, including automating repetitive processes, generating geometry through mathematical functions, quickly making changes to complex models, and creating complex forms through repetitions of simple geometry. Grasshopper requires no programming or scripting knowledge, but still allows designers a high degree of flexibility in creating both simple and complex forms (Reilly, 2014).

In this dissertation, the software used was Revit® from Autodesk® and its extension Dynamo®. Autodesk is one of the most commonly used software throughout the construction industry around the world, according to the BIM report made by NBS in the UK in 2019 (NBS, 2019).

2.1.4 Interoperability

The BIM industry is currently thriving and in constant evolution, and the need for interoperable data for easier transfer is being sought out through professionals throughout the industry for its importance, due to the existence of various software vendors. With the existence of so many platforms for modelling and data processing, it is imperative that the information to be used is transferable to an universal format that allows its transfer to multiple platforms (Ma & Ren, 2017).

The interoperability between software is defined by the ability of communication and interaction for multiple software components written in different programming languages. There are three different types of interoperability: between the software of the same vendor, between different vendors and the most efficient type is through open data standards (Nielsen & Madsen, 2010).

The first type has no major issues as the vendor has access to all the needed requirements to make the transfer of information efficient and operative from one software to the other, yet this does not ensure the continuity of the information in the long term since this process is not public. The second type requires the presence of a middle software to convert information from one software to another that uses BIM, however, with the presence of so many software this process is inefficient. The third type, which is through open standards, is the only type ensuring the continuity of information for the long term, and it is the most efficient type as information can be shared between different stakeholders, regardless of the platforms they are using.

2.1.4.1 Open Standard BIM

OpenBIM is the ability to interpolate data through open standard formats between the software of different vendors. It increases the benefits of BIM by improving accessibility, usability, management, and sustainability of digital data in the construction industry. This collaborative process is vendor-neutral and its processes can be defined as sharable project information that supports collaboration between all project participants. It facilitates interoperability which increases benefits to projects and assets throughout their lifecycle (buildingSMART, 2020).

OpenBIM extends the breadth of the use of BIM by creating common alignment and language that is adhering to international standards and working procedures. It greatly enhances collaboration for project delivery and provides access to BIM data created in the initial phases of a project for the whole lifecycle of the built asset. OpenBIM permits digital workflows based on formats that are vendor-neutral such as Industry Foundation Classes (IFC), BIM Collaboration Format (BCF), Construction Operations Building Information Exchange (COBie), CityGML, Green Building XML (gbXML), LandXML, etc…

2.1.4.2 IFC

For this work, the focus was on IFC exports, as it is one of the main and most used open data standards used to describe construction, building, and architectural data according to the BIM report made by NBS in the UK in 2019 (NBS, 2019). IFC was standardized by the ISO, in the standard ISO 16739-1: 2018, which allows the construction industry to benefit from a common language to export and import data. IFC is a digital description of the built environment, including buildings and civil infrastructure. It is meant to be vendor-neutral and usable across a wide range of hardware devices, software platforms, and interfaces.

The Industry Foundation Classes specify a data schema and an exchange file format structure. The data schema is defined in EXPRESS data specification language, defined in ISO 10303-1, and XML Schema definition language (XSD), defined in XML Schema W3C Recommendation, whereas the EXPRESS schema definition is the source and the XML schema definition is generated from the EXPRESS schema according to the mapping rules defined in ISO 10303-28 and ISO 16739-1:2018. IFC files logically build the model by creating a building model based on a pre-defined structure. After saving, the IFC file format orders the IFC units hierarchically according to their type (see fig.13).

The IFC standards mainly targeted building information and rapidly extended to include the infrastructural construction as well. Current infrastructure IFC development will help fill in the present gaps in BIM for infrastructure, however, there is a need for an unambiguous naming and description of built environment conceptual objects. This needs to cover the multiple domains associated with the built environment from rail engineering through road and hydraulic engineering, groundworks, and the environment (Jackson, 2018).

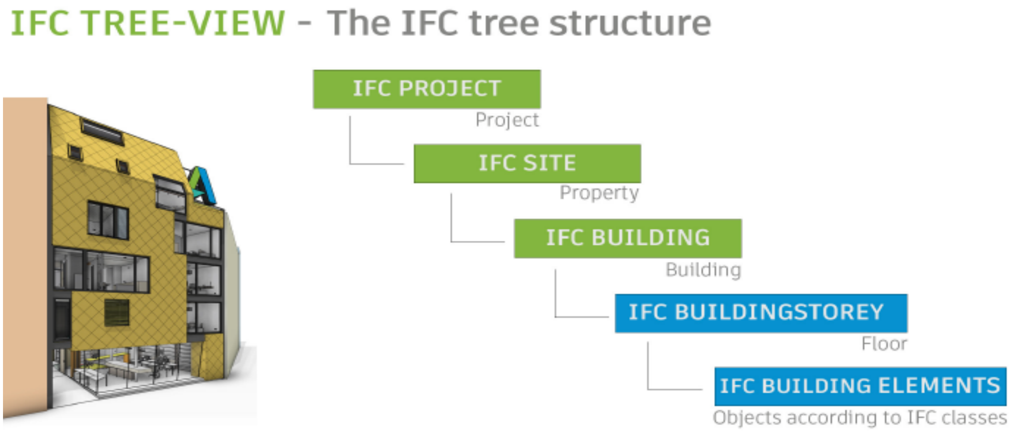


Figure 13: IFC-types tree structure from Revit IFC manual (Autodesk, 2018)

In regards to common data formats for infrastructure, even though different examples of integrating various datasets and data formats exist, there is no common data format (like the IFC) fully extended to encompass the major types of infrastructure projects like transport, utilities or environmental projects. Hence the work towards a universally agrees conceptual data structure is a very important area for future research (Bradley, Li, Lark, & Dunn, 2016).

The current situation of IFC does not allow for a perfect transfer of information between software from different vendors as a smooth operation unless the information provided is well documented and includes all necessary data from all stakeholders. The main purpose of this standard is exchange model information between different stakeholders, but because of the different kinds of information needed from different stakeholders, it is difficult to assume that all needed information has been preserved in this process from the initial model, yet with the standardization of processes and data management, the interoperability of data can become more efficient.

2.1.5 The move of BIM from buildings to infrastructure

2.1.5.1 A look into the literature

It is relatively important to note that a review of the literature has indicated a lack of attention towards infrastructure and that most of the research is focused around the construction sector (Bradley et al., 2016) (see table 1). However in the past couple of years, there have been many changes in Information modelling in the infrastructure sector, and it is receiving the attention it deserves as professionals and researchers continue to prove the benefits of implementing BIM in infrastructure (Morin, Hassall, & Chandler, 2014), the increased pace of publication on the subject can be witnessed in the plot of figure 14 (see fig. 14).

Table 1: adapted from Initial volume returned for the literature search exercise (Bradley et al. 2016)

	Scopus	Engineering Village	Science Direct	Web of Science	Totals
BIM infrastructure	50	71	11	46	178
BIM construction	1057	901	183	675	2816
Totals	1107	972	194	721	2994

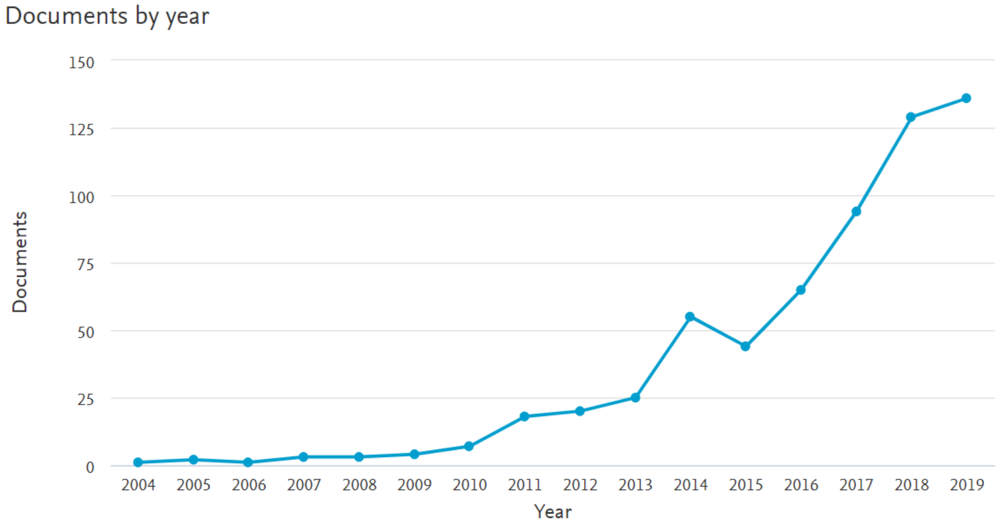


Figure 14: Documents per year search results for keywords (BIM and Infrastructure) (Scopus, 2019)

BIM extension specifically into the geotechnical engineering sector of infrastructure is a subject that is seldom given the right attention in research as the number of publications in this subject is not very significant compared to the general number of publications for infrastructure (see fig. 15), and this lack of attention results in unwanted problems that affect costs and schedules and reduces the efficiency of using geotechnical data extracted in the beginning phases of a project. Underground unexpected conditions have been proven to be one of the main risk factors in projects causing delays and overspending. Reducing the risk of these problems should be a major concern during the geotechnical design process (Morin et al., 2014, Clarke, 2004, Atkins, 2006, Staveren, 2006, Fenton and Griffiths, 2008, Royse et al., 2009, Caers, 2011).

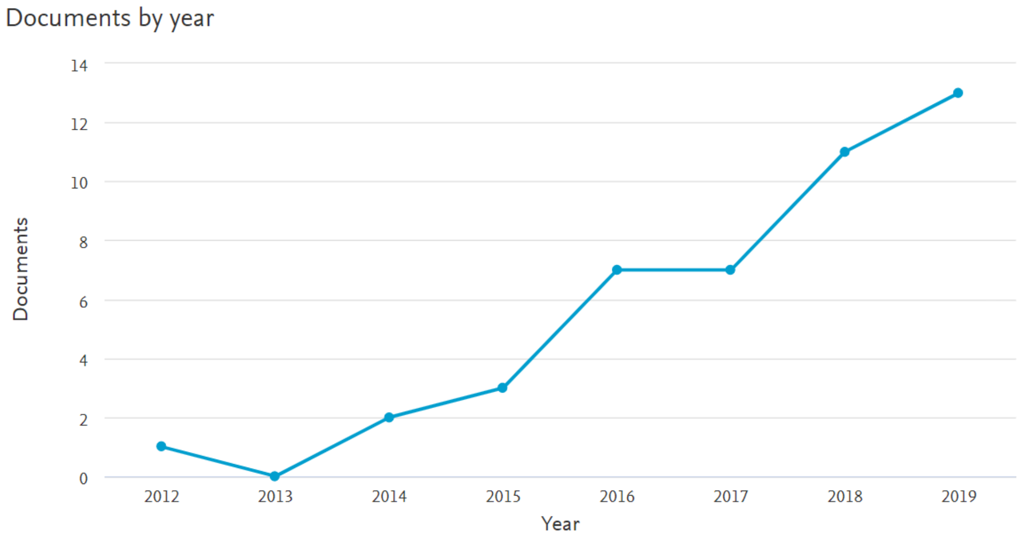


Figure 15: Documents per year search results for keywords (BIM and Geotechnical) (Scopus, 2019)

The geotechnical engineering community agrees that the implementation of BIM processes into the geotechnical engineering process will result in positive impacts and the integration of geotechnical data in an interoperable format may improve the design and management process in regards to finance and time factors. But the efficiency of this integration depends on the quality of ground investigations and the ability to include the resulting information in an authoritative and interoperable format and the availability of this information in databases (Tawelian, Mickovski, 2016).

Many efforts have been made in the path of improving the way geotechnical information is managed and represented (Tegtmeier et al., 2014, Chang, & Park, 2004, Toll, 2007, AGS, 2012, Choi et al., 2009, Kramer, 2010, Zhang, et al., 2016, Kim, & Gultekin-Bicer, 2018). However, most of the developed models and data structures are either application-specific (e.g. for the management of slope or borehole data), or kept on a more general and 'geology-wide' level, or not developed to be easily integrated into BIM platforms.

2.1.5.2 Current development of BIM in infrastructure

BIM started in the AECO industry to bring a different process of collaboration and a new way to transform the way the industry works and functions. The concept of BIM has become the main topic for improving the AECO industry, as the complexities in projects increases and the time for completion decreases, there is more reliance on information and communication technology, and the transition to BIM processes is significantly increasing. The use of BIM is crucial for infrastructure projects to be able to handle the highly complex and diverse nature of project requirements specifically in road/highway, tunnels, bridges, and other similar construction (see fig. 16).

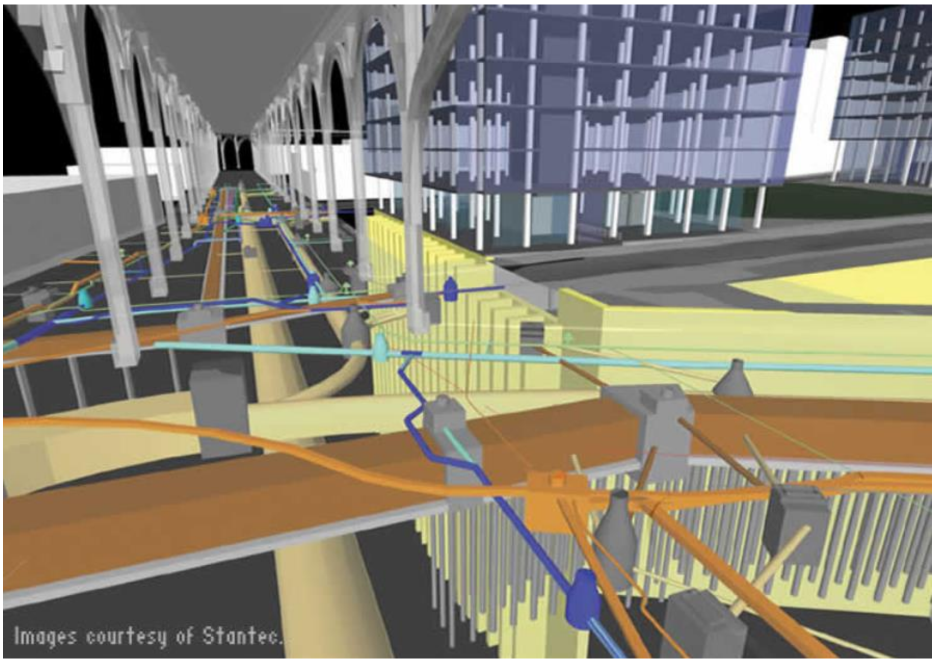


Figure 16: View showing the complexity of subgrade utilities in an infrastructural project (Autodesk)

There has been a great shift in technologies, which was previously used in the building sector, into the infrastructural sector. Technologies that support the use of BIM and is key in improving the way data is collected and projects are visualized. 3D laser scanning and Point cloud mapping technology for example is being utilized for surface/terrain generation from high-resolution point cloud data in infrastructural projects and used for the preliminary and detailed infrastructural design (Grover, & Sridharan, 2016) (see fig. 17).

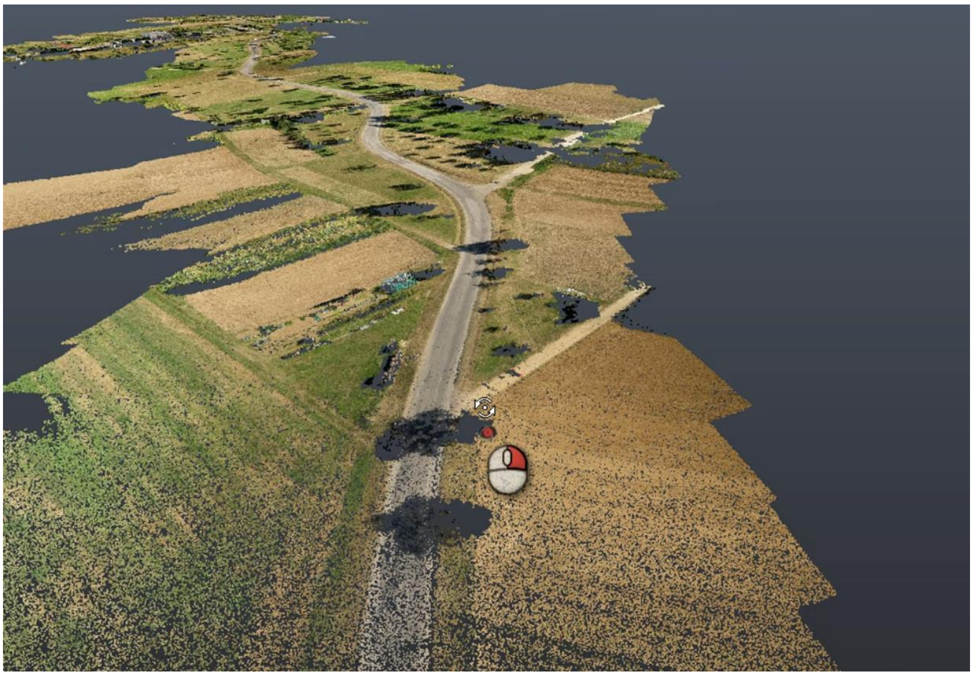


Figure 17: Point cloud terrain model (Classon, 2018)

Virtual reality (VR) and augmented reality (AR) have also become the future of project visualization and a key solution to visualizing complex projects (see fig. 18). Augmented Reality has been a subject of discussion on how it can help prevent damage to underground utilities during infrastructural works, especially in the beginning phase of a project during the excavation phase (Stylianidis, et al. 2020). In water infrastructure, it showed great potential in increasing the efficiency of mobile workforces, thus revolutionizing traditional planning, operation, maintenance, on-site inspections, and general decision-making methodologies (Schall, Schmalstieg, & Junghanns, 2010).

Figure 18: View through the AR display showing underground infrastructure (vGIS, 2020)

Virtual reality is a factor in accelerating savings in complex infrastructure and construction projects. It also has significant potential to increase the quality of projects, and unlock further benefits for the client, because it provides a real sense of scale, functionality and user experience (Sekse, & Storm Emborg, 2019).

This technology however is still relatively new to infrastructure, but it is being used more and more in different projects around the world. An example of implementing this technology is the Norwegian Rail Project (Mcmanamy, 2017), where VR is being used to help the project team design, visualize, and negotiate environmental complexities and as well as help foresee potential design problems. Train operators drove on the virtual train tracks under the supervision of civil engineers, who used their performance to evaluate the placement of signs and signals (see fig. 19).

Figure 19: Train operator driving in a simulated cockpit using VR (Autodesk)

Many countries across the world have already adopted BIM, and some countries currently mandate the use of BIM on projects or have released formal standards. Most of these standards focused more on buildings in the first years of adaptation, but shortly these standards moved to infrastructure, as the realization of its benefits increased.

With the development of BIM in infrastructure, standards and specifications (e.g. ISO 19650 & PAS 1192) for working with BIM also developed, as mentioned earlier, to reach the infrastructure sector with the definition of the levels of information, levels of detail, levels of development, and interoperability requirements for the different phases of projects. This extension of development did not only affect the structural part of the infrastructure sector but also stretched out to reach the works done in the fields of geotechnical engineering related to subsurface layers.

This movement changed the way geotechnical data is handled in infrastructural projects (RailBaltica, 2019, MTHojgaard, 2016), where it became necessary that all geotechnical data be presented in BIM friendly interoperable formats and to be integrated into the BIM platforms as 3D elements (see fig. 20), and also defined the level of development of the geotechnical models in different phases of the projects (see fig. 21).

Model type	Content	Format
Existing subsurface	Indicative model of existing geological layers based on information registered in geotechnical investigations. Geotechnical investigation results for each borehole shall be defined and described in 3D coordinated files with descriptions and technical parameters of the soils as included attributes/layers The results for the investigations shall be presented in a form that will allow the use of the results in B(uilding) I(nformation) M(odelling) (BIM). This requires the data to be sufficient to build a 3D-subsoil model. It should be possible to build a surface for each defines soil layer. For this to be possible the top and bottom absolute height values must be available. The surface can then be able to be exported as a mesh. In case of soil lenses, those shall be able to be shown as a polygon.	DGN/DTM DWG/DXF/XML IFC2x3 (IFC4)

Figure 20: Requirements for existing conditions from an infrastructural rail project (RailBaltica, 2019)

COMPONENT			LEVEL OF DEFINITION			
Category	System	Description	200	300	400	500
Geotechnical	Ground Conditions	Existing Ground Conditions	3D CAD Models of: • Boring Locations • Lab test results (DG soil classification) • Test Pit Locations • DCP locations • Terrain model • Ground Water Profile	incl. LOG 200 and additionally: • Additional Boring Locations • Additional Test Pit Locations • Additional DCP locations • Updated Terrain model Detailed 3D Interpreted Component Models of: • Strata Profiles (including ground water level/profile and assessed Highest Water Level HWL by DTD) • Embankment and cuttings subgrade (including soil/material QS classification according to DG)	As LoG 300 • Updated overview of materials used in subgrade, embankment, sub-ballast, ballast layers	As LoG 300

Figure 21: Levels of Definition of geotechnical works from an infrastructural rail project (RailBaltica, 2019)

The positive result of implementing BIM has been visible during the past decade. A few examples can clearly show that the BIM implementation yielded great results (Berdigylyjov, & Popa, 2019). Noteworthy examples, in particular, would include the maintaining of subway tunnels (Marzouk and Abdel-Aty 2012), integration of BIM in motorway projects (Dave, Boddy, & Koskela, 2013), prototype development of GIS to be used with BIM in planning design and construction (Borrmann et al. 2014), as well as open information transfer in the road, railway, and watercourse construction projects (Heikkila et al. 2013). One of the successful examples of how geotechnical data was used in a BIM context is the Silvertown Tunnel executed under the River Thames in East London (Morin, Deaton, Chandler, & Miles 2017).

Simon Miles, a senior geotechnical engineer, in Atkins, working on the Silvertown Tunnel project stated: "*The use of a fully integrated, multidisciplinary Civil 3D model, including subsurface geology, has been a real eye-opener for the team. By visualizing ground conditions in a design context, we can reduce project risk and project costs during construction*" (Morin, 2019). The project's complexity lied in the many unseen elements that posed a risk to the work from different ground conditions, roads, foundations, and other subsurface structures (see fig. 22).

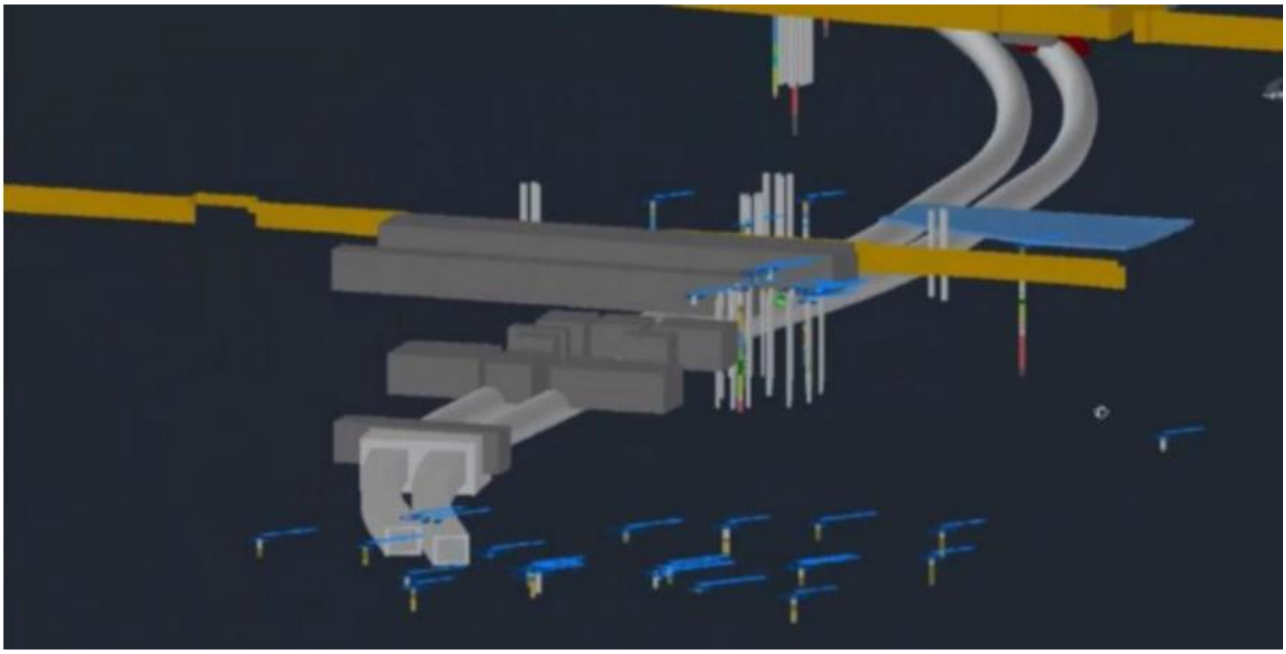


Figure 22: 3D Boreholes and possible obstructions (Morin, 2019)

Geotechnical engineers decided to develop a 3D ground model of the site and ground conditions to help them overcome the obstacles they were facing (see fig. 23). The engineers used Holebase SI extension for Civil 3D to model geological layers of the subsurface directly from the available geotechnical data, and that aided the project team to visually understand and estimate the design alignment, accurate construction obstructions, and decide what new site investigations were needed.

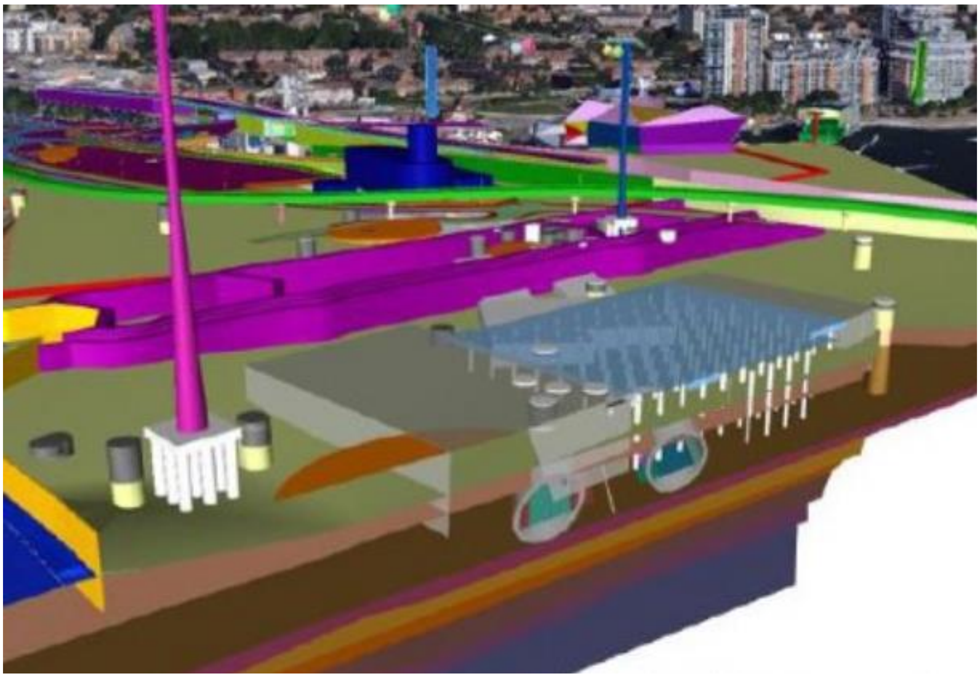


Figure 23: The combined geotechnical model (Morin, 2019)

This resulted in the rapid adaptation of the combined geotechnical model as geotechnical information was added, and it reduced the number of boreholes necessary for the site investigation which reduced project time and cost.

2.2 Data flow in geotechnical engineering

2.2.1 Geotechnical investigation

The main purpose of the geotechnical investigation is to facilitate the adaptation of a construction project to the worksite it is located on, to limit the natural and induced risks. It is performed to transfer the information related to the nature and behavior of the site to the developer and builders, so they can define and justify the technical solutions they will develop and implement to finalize their works efficiently and with the least amount of risks (Martin, 2008).

Geotechnical information is very important to determine a site's suitability for a given building or infrastructure project, safe and economical design, and adequate execution of the project particularly when the land has a poor geologic condition. The geotechnical investigation is the principal way to get the required geotechnical information from the results of laboratory and in-situ tests. It is the process of collecting, processing, analyzing, and presenting geotechnical data. It is a heavy workload process where geotechnical data is collected (see fig. 24), geological maps are compiled, and data is analyzed. The result of this process is the geotechnical investigation report (see fig. 25) (Arnous, 2013).

BOREHOLE DRILLING DATA SHEET				Borehole No.		Page __ of ___	
Project No.		Project Name		Site Name		Supervisor	
Start Date		BH location		Surface RL		Groundwater RL	
Finsih Date		Drilling Contractor		Driller		Drill Rig	
Contractor		Water Truck		Water Load Vol.		Security	
Drilling method	From Depth	To Depth	TCR	RQD	Sample no.	SPT N Value	Material Description
Time Log							
Date	From	To	Activity	Date	From	To	Activity
Summary of Quantities							
Casing(m)		SPTs No.		Core Trays No.			
Soil Drilling(m)		Consumed Drill Bits		Shear Veins No.			

Figure 24: Adapted from TMR borehole drilling data sheet (TMR, 2019)

The geotechnical data workflow in civil engineering projects commonly starts with a geotechnical subcontractor that performs the necessary works, tests, and analyses to produce the geotechnical investigation report. Sometimes 3D programs are used to integrate the data into a single model then it is transferred to the engineers in the report with the digital model, cross-sections, and drawings of the subsurface. This information is normally reviewed by someone with geological knowledge and the data is simplified to serve the purpose of the infrastructure part of the project like the design of foundations, piles, anchors, and other underground works.

After that phase of using the essential data for the project, most of the unused information of the subsurface is ignored. The data collected is seldom integrated with the project model, mainly because of the difficulty in integrating geotechnical data and model in the projects modelling platform. Another issue that arises also in big projects is the lack of re-use and exchange of information because the information is not standardized and made in the same structure, format, and with the same naming, and also because the quality and uncertainty of the information is not quantified (Tegtmeier, Oosterom, Zlatanova, & Hack, 2009).

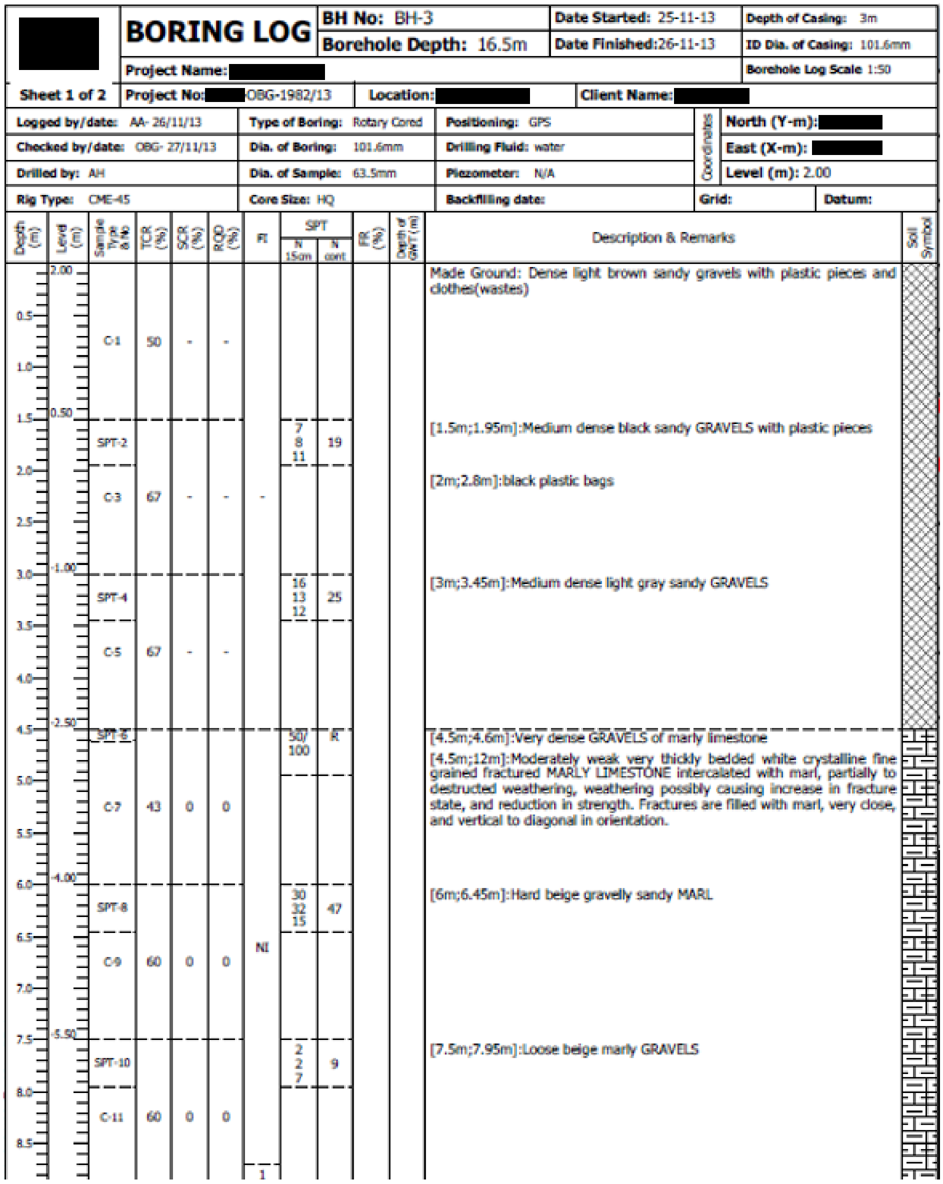


Figure 25: Boring log part from the geotechnical investigation report

Any future projects in the exact location would entitle rework to recollect the same necessary information, which results in losses in time and money. The integration of subsurface data in the construction model is very advantageous for construction projects, whether in the planning, designing or execution phase (Tegtmeier, et al., 2014, Culshaw, 2005, Fookes, 1997, Hack, 1997, Hack et al., 2006, Yanbing et al., 2006, Nisa Lau, et al., 2018).

2.2.2 The traditional vs. BIM approach to the geotechnical investigation process

2.2.2.1 Traditional approach

The traditional journey of geotechnical information (see fig. 26) is a work-intensive process as mentioned earlier, and it is characterized by its linear waterfall process, where one stage ends, the other starts. The process starts with site exploration where a surveyor normally takes coordinates of the site and creates the topology of the surface. Then a phase of sample collection takes place and laboratory testing is made to collect data of the underground layers, this data is then used by the analysis center to create the geotechnical report with borehole data and 2D drawings of sections.

After that the engineer analyzes this data and inserts it into a digital platform for the creation of 2D or 3D presentations for better visualization, this data is used in analysis software for design purposes. If the engineer finds that additional data is needed, the same process is repeated from the collection of data from the site until the creation of new 2D or 3D presentations to performing new analysis to attain the needed results. Finally, all the collected data is stored in a paper-based document in the national or local archive, and hardly ever used again.

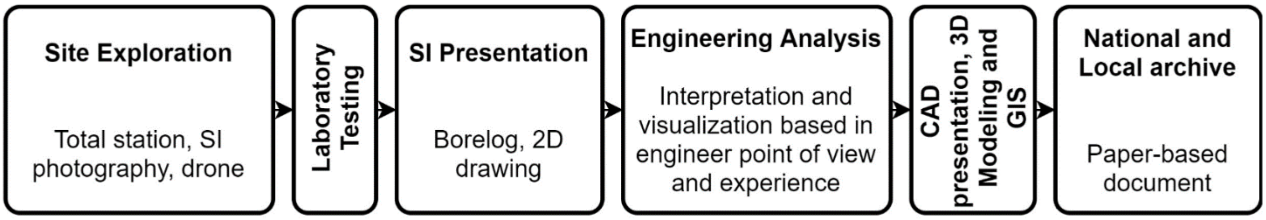


Figure 26: Traditional Approach (Child et al., 2014)

This process makes the move back and forth between stages difficult resulting in a lot of re-work and time loss. With the passage of data occurring at clear phases of the investigation, much data are often not retained or reused, which decreases efficiency. Moreover, dividing the process into isolated stages leads to many delays in processing data from one stage to the next, and these multiple transitions of data increase the probability of errors (Child, Grice, & Chandler, 2014).

With the advancement of computer information systems (CAD and GIS), new ways of digitization to improve the efficiency of the process of geotechnical investigation is being researched. Currently, many approaches based on information systems have been proposed to improve the efficiency of geotechnical investigation, of which many had fruitful results (Ramanathan, Aydilek, & Tanyu, 2015; Yeniceli & Ozcelik, 2015). Most of these approaches can be put under the broad titles of CAD and GIS-based approaches, where the former aims to compile geological information in a geological map using electronic drawing platforms, the other seeks to handle and analyze data in a spatial perspective.

These approaches can improve the geotechnical investigation efficiency, but both of them divide the process into isolated stages and pay minimal attention to the overall process of the investigation, which results in limited improvement of the efficiency of the geotechnical investigation process. Hence, any change to the investigation scheme would result in the repetition of works, regardless of if the work is assisted by information technology or not. This approach does not pay attention to the coordination between the different stages of a geotechnical investigation, which results in misuse of geotechnical data, information silos, and misinterpretation of results (Zhang et al., 2016).

Several works can be found in literature concerning approaches for three-dimensional geotechnical modelling, but little can be found on the general approach behind using a three-dimensional geotechnical model to reform the geotechnical investigation process (Jia, et al., 2015, Mathers, et al., 2014). Furthermore, analysis based on the three-dimensional geotechnical model ignores the related geotechnical data and that makes the accuracy of the interpreted results lower (Thanh, & Smedt, 2014).

2.2.2.2 BIM approach

The BIM process involves the generation and management of digital representations of the functional and physical characteristics of a project (Xu, Ma, & Ding, 2014). It makes sharing of data easier for different teams of a project so they can work more efficiently together in a more collaborative manner (Kubota & Mikami, 2011). However, Three-dimensional representation of elements does not mean a process is a BIM process. BIM is much more than modelling, it is a process to improve the collaboration between different parts of the AECO industry along with stakeholders and final users of projects. It is the process of creating a data-rich, intelligent, object-oriented, and parametric digital representation of objects.

The implementation of this methodology in the geotechnical part of any project will result in higher efficiency and accuracy in the use of geotechnical data (Mignard, & Nicolle, 2014, Gondar, Pinto, & Fartaria, 2019) and it has proven to be an efficient methodology in saving time and money in different types of projects in different locations around the globe (Berdigylyjov, & Popa, 2019).

The use of a BIM-based workflow which is a data-centric annular process (see fig. 27), will improve the efficiency in time throughout the investigation, and since the data is stored in a BIM database, there will be no transmission of data in the future which will decrease errors and increase efficiency. This BIM process is divided into eight different stages (Zhang et al., 2016):

1st stage is the preparation phase. It involves the process of preparation of the preliminary 3D geological information model by reviewing the existing information and the results collected from a site survey, like a simple model of the site's surface and the basic geological maps available.

2nd stage is the creation of the investigation scheme and its specifications according to the norms and standards depending on the site's location.

3rd stage is where the engineers organize the execution of the necessary procedures to collect geotechnical data, according to the preliminary investigation scheme, and to perform the necessary field exploration and sampling and deliver the geotechnical data to the analysis center.

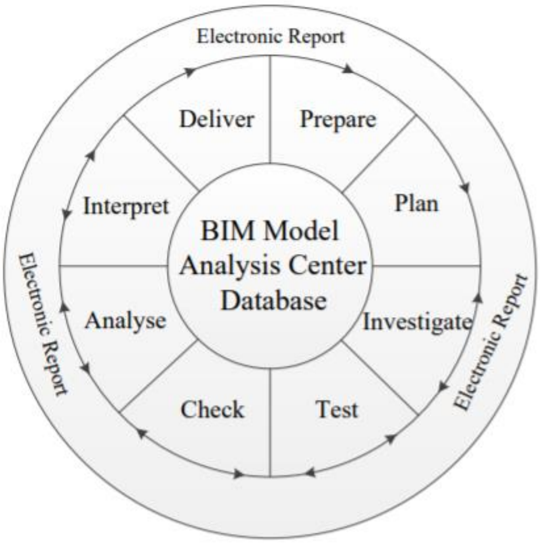


Figure 27: The workflow and data journey of BIM-based geotechnical investigation (Zhang J. et al, 2016)

4th stage is in synch with the 3rd stage, it is where the samples collected undergo several tests in a laboratory and the results gained are integrated with the rest of the collected geotechnical data in the analysis center.

5th stage is done in the analysis center, where geologists analyze the validation of the data and remove the conflicting ones. They also use laboratory test results, expert database knowledge, and geophysical exploration data to enrich the 3D geological information model from stage 1. This includes the modelling of the boreholes, trenches, water wells, and the like in the 3D model to create the geological structure and exploration object of the studied area, which can help in obtaining an overlook of the subsurface when the results are interpolated. The results of this work are then analyzed and the investigation scheme from stage 3 can be updated accordingly.

6th stage is the repetition of stages 3 to 5, to minimize production tasks and improve the timeframe of the investigation period in conformity with relevant specifications to attain more accurate results.

7th stage is comprised of the creation of statistical reports, 2D drawings (cross-sections, stereographic projections, etc…), extracting sub-information models, and so on. This task is performed by the geologist and technical staff in the analysis center.

8th stage is the data delivering phase of all the data collected and analysis done, combined in an electronic report. The importance of the electronic report is that it facilitates the reuse of geotechnical data.

As the timeline of the project moves forward, data is accumulated in the data-centric BIM approach and not transferred from one entity to the other like in the traditional approach, and the boundaries between the phases of the geotechnical process are blurred. In this process, geotechnical data is stored in a BIM database after being generated, and the exchange of information and data transmission that happens in the traditional approach seizes to exist. This results in higher accuracy and better data preservation (see fig. 28).

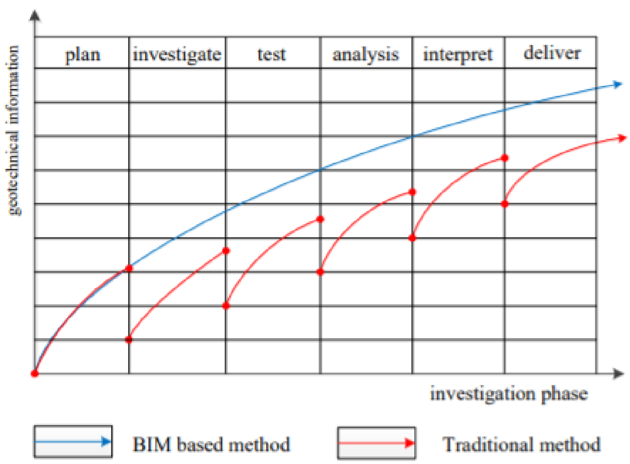


Figure 28: The comparison of the accumulation of geotechnical information in the BIM and traditional approach (Zhang J. et al, 2016)

It is important to mention that the use of the BIM process instead of the traditional process, even though it seems like it could incur extra costs on projects, actually helps in saving costs taking into consideration the whole lifecycle of the process. By improving the accuracy and quality of the generated results and by ensuring no data loss or rework will take place, the BIM approach proves to be economic and efficient. A comparison of the workload done on a project using both processes shows that the BIM approach is efficient and economical (see table 2).

Table 2: Workload comparison of the geotechnical investigation in a hydropower station project between BIM and traditional approaches (adapted from Zhang et al., 2016)

Content	Specification	Unit	Traditional method	BIM method
Topography measurement	1.430555556	Km^2	15	15
Geology surveying	1.430555556	Km^2	15	15
Section geology surveying	0.111111111	Km	8	8
Points setting out	-	Ea	400	360
boring	-	m/bore	6675.73/59	5638/59
exploratory tunneling	-	m/adit	2678/18	3015/18
geophysical approach	Adit seismic waves	m/adit	1937/17	1612/17
geophysical approach	Adit sound waves	m/adit	922.0/8	834/8
geophysical approach	Borehole soundwaves	m/bore	2626.0/39	2208/39
geophysical approach	Borehole TV	m/bore	1461.62/13	1304/13
geophysical approach	Seismic section	m/piece	5755/20	6107/20
high-pressure water test	-	segment	1063	1045
pumping test	-	segment	4	4
Water quality analysis	-	group	7	7
Physical and mechanical properties of rock	-	group	41	36
Rock slice identification	-	block	5	5
Fault classified	-	group	6	6
Rock deformation test	-	point	29	18

2.2.3 Current BIM software for Infrastructural and geotechnical engineering

2.2.3.1 Software for Infrastructure

As the use of BIM in the AECO industry came into demand, different vendors have introduced different tools for the implementation of the BIM methodology in infrastructure, architecture, structure, MEP, performance analysis, and facility management. As this work is directed toward infrastructure, it is relevant to mention the software provided by some vendors for different infrastructural works:

- Autodesk: AutoCAD; InfraWorks; AutoCAD Civil 3D; Revit; Navisworks; BIM 360; Structural Bridge Design; Robot Structural Analysis Professional; ReCap Pro; and Dynamo Studio.
- Bentley: MicroStation; OpenBridge; OpenRoads; OpenSite; Plaxis, gINT, SOILVISION; OpenGround; Keynetix; and ProStructures.
- Tekla and Trimble: Tekla structures, Tekla Structural Designer; Tekla Civil; and Tekla Tedd.

These software are used in the design and modelling of tunnels, roads, and other types of infrastructural projects. Few of these software provide an all in one software that can perform all the required modelling and performance analysis in one platform, and most of the time it is required to move data from one platform to another for analysis purposes, or if it is to be handled by a different entity using different software. Hence the interoperability between software is necessary to perform any required data movement. However, the interoperability between software of different vendors, is not such an easy and smooth operation as mentioned earlier, even with the presence of open data formats for information exchange.

The mentioned tools are good for the creation of models and engineering analysis. However, focusing on the models created in BIM platforms, where all the project collaboration between stakeholders takes place, they seem to ignore the geotechnical aspect of the work and the geotechnical model representing the subsurface is scarcely integrated into the BIM model of a project, which causes costly mistakes (Eastman, Jeong, Sacks, & Kaner, 2009). The main difficulty lies in the extracting and assimilating of archived geotechnical data between the BIM platform and the data provider (Zhang et al., 2018). Studies show that there is a lack in the re-use of geotechnical data and it is one of the major causes of project delays and overspending (Parry, 2009). Much research has been made to explore the workflows for incorporating geotechnical information in the BIM process. There is a direction indicating the existence of a gap in building a multi-scale informative geotechnical model (Zhang et al., 2018). Research has proven that the geotechnical information of the subsurface if were to be used and collected in a BIM transferable way will be of great benefit to the industry in many aspects (Tegtmeier et al., 2014).

Based upon the above information, it was intended the exploration of the available geotechnical engineering software, that support the use of geotechnical data in BIM platforms, whether through direct applications in the BIM platform or any other software that exports geotechnical models in open data formats for interoperability with the BIM platform.

2.2.3.2 Software for geotechnical engineering

Many geological survey organizations are making geological information and open digital resources publicly available (UK: BGS, 2020, Catalunya, and USA: USGS, 2020), however, this information is found either in GIS platform as scanned paper documents or digital documents and not in a BIM-based digital format (see fig. 29).

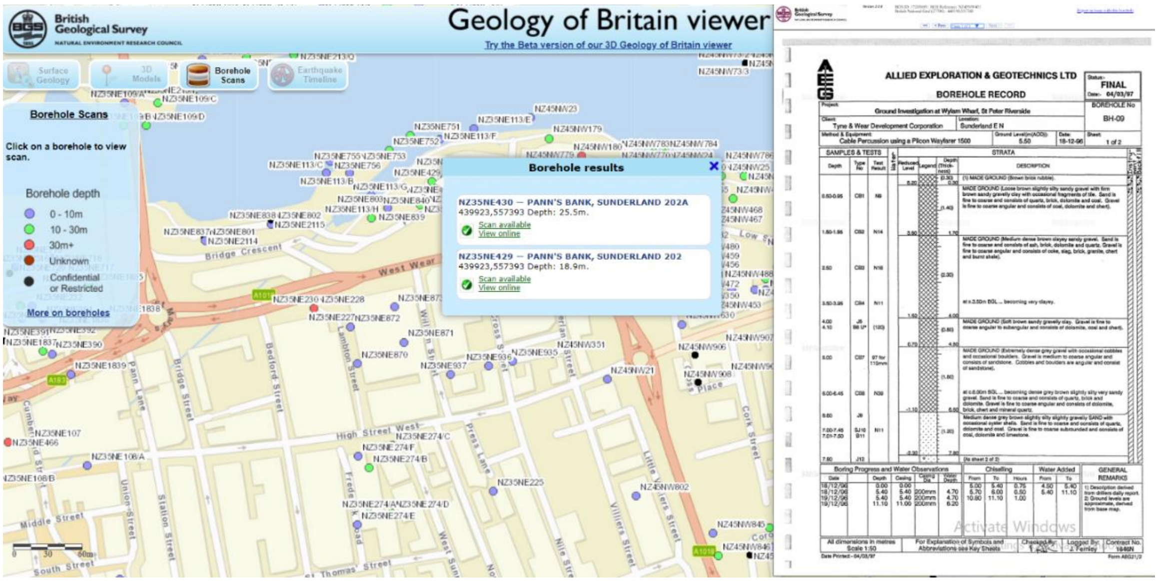


Figure 29: Borehole geotechnical reports as scanned documents in an open digital resource in the UK (BGS, 2020)

Some organizations tried to deliver a 3D model of the subsurface (DINO, 2020; BGS3D, 2020) (see fig. 30), however, it is not in an exportable format to BIM platforms, which means the transfer of this information would be an extensive process.

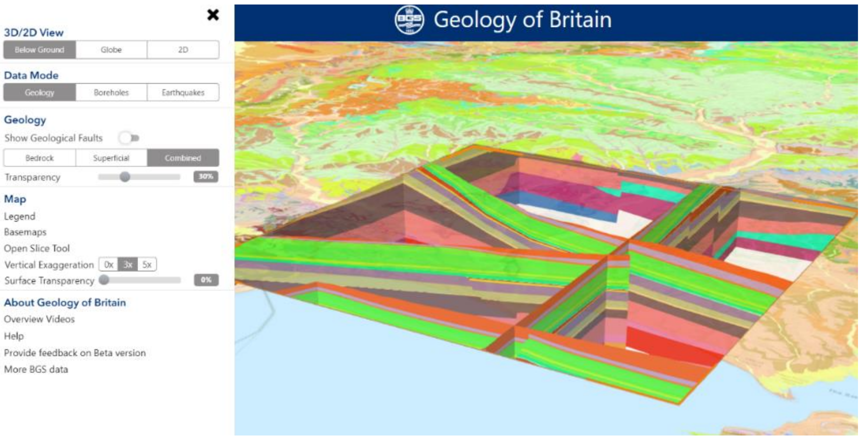


Figure 30: section showing the 3D distribution of subsurface layers based on borehole data in a digital open resource in the UK (BGS3D, 2020)

There has been a great development in geotechnical analysis software for the possibility of 3D modelling of underground elements and the sharing of models in open data formats that allows the models to be transferred into BIM platforms. The main purpose of these software is to make it easier to visualize the subsurface layers to improve the design and decision-making process and make it faster (see fig. 31).

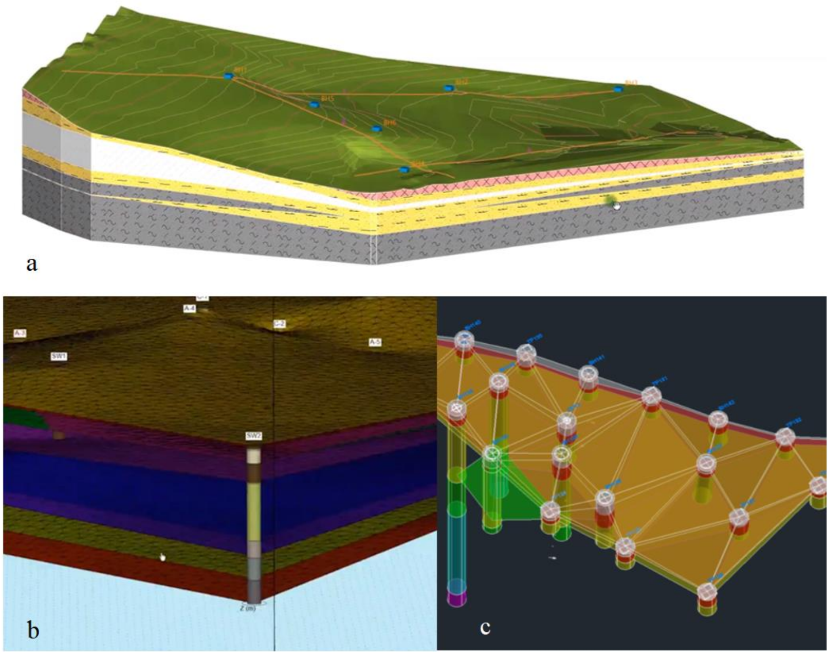


Figure 31: Subsurface modelling based on borehole data in (a) GEO5 (Fine, 2019), (b) SVDESIGNER (Bentley, 2002), and (c) Holebase SI (Keynetix, 2019)

A rough analysis was made on some of the existing software which models the subsurface layers in 3D using geotechnical information derived from borehole drillings and geotechnical investigation reports. The analysis was done based on information that can be found online on the software official pages and other online resources. The following information was collected for each software analyzed (see table 3):

Autodesk's Civil 3D extension "Holebase SI" from Keynetix, which has been recently acquired by Bentley, is a tool that takes geotechnical data related to borehole drillings to create a 3D model of the subsurface layers. It uses coordination and depth data to model the boreholes and subsurface layers. It is possible to include in the model in the extension geotechnical data, however, this data is not linked directly to the modelled elements, hence when exporting the data to the BIM platform only limited data can be attached to the modelled elements.

SVDESIGNER from the SoilVision series of Bentley is a tool to model the subsurface in 3D. It is possible to attach data related to piezometer readings with the model. The model can be exported to other software of the SoilVision series, however, it does not export to open data formats.

Geo5 from Fine is a tool that allows the 3D modelling of subsurface layers based on borehole data. It also allows the inclusion of several parameters from site tests like SPT, DPT, CPT, PMT, and DMT. It also allows the export of this information into IFC and hence the possibility of importing it into a BIM platform is possible, however, this process is not as seamless as Holebase SI since the latter exports the data to a BIM platform of the same vendor if the BIM platform used is Revit.

Table 3: Comparison between software that 3D model the subsurface based on borehole data

Software Name	Vendor	Does it provide a 3D model of the subsurface ?	Does the model integrate borehole and geotechnical data from the geotechnical investigation report?	Is it a BIM platform ?	Does it export to open format (ex. IFC)?	Is the transition of model and data to the BIM platform easy?	Is there any mention of standardizing the geotechnical data from boreholes in the model?
Holebase SI for Civil 3D	Keynetix / Bentley	Yes	Yes	No	3D model (Yes) / Geotechnical data as parameters of the model (No)	Yes	No
SVDESIGNER	SoilVision / Bentley	Yes	Piezometer data	No	No	No	No
GEO5	Fine	Yes	Layer description / SPT / DPT / CPT / PMT / DMT	No	Yes	No	No

The interoperability between software and BIM platforms, in general, is not seamless and could require the use of multiple platforms to perform the task, which involves the risk of losing valuable geotechnical information related to the modelled underground layers and materials (Osello, Rapetti, & Semeraro, 2017).

Most of these software also does not allow the possibility of including all the geotechnical information derived from geotechnical reports in the modelled layers as parameters and only requires coordinate and material information for modelling the subsurface. In some software, it is possible to add all geotechnical information in the model in the main software, but when the 3D model is exported to the BIM platform it does not migrate all the geotechnical information as connected parameters with the created elements (boreholes and subsurface layers). This means that the final geotechnical model integrated into a project's BIM model might not have all the information needed for future use, and the risk of loss of information or re-work increases.

Based on this information, it was intended to create a direct extension to the BIM platform Revit, using Dynamo, which allows the possibility to create a 3D model for the subsurface layers based on borehole data and the information taken from geotechnical reports. The modelled elements would include all the possible parameters that can be found in a geotechnical report that would be of use for any user of this model. This will be proposed through the use of PDT for standardizing borehole data. The produced model even though it would be already created in a BIM platform, will be discussed the possibility of exporting it in an open-source format, like IFC, for interoperability purposes.

3 PROPOSAL OF PRODUCT DATA TEMPLATE FOR BOREHOLES

As mentioned earlier, the importance of standardization in the field of construction holds many benefits and helps in the unification of data used to describe objects that are present in BIM platforms. From that perspective, it was needed to create a standardized template for the geotechnical data related to subsurface layers. Since the main element that contributes to the extraction of underground geotechnical data is a borehole drilling and the investigation that follows it, and that this element can be represented in the BIM platform as an object, it was proposed the creation of a PDT for the BIM object representing the borehole.

3.1 Collection of parameters

For a PDT to be a complete document, it should hold benefits for all stakeholders that are involved in using it. Hence it is imperative to take into consideration all the stages where this data will be used and who will use it. The stages and users of this PDT will define the amount of data present in it, based on the recommendations found in standards related to geotechnical information or based on project requirements.

The level of development related to subsurface layers does not require a high level, as the purpose of the 3D model is to indicate the ground layers distribution in a specific location, vertically and horizontally and there are no detailed drawings necessary after that visual information is clear. The model is used to help the engineers and other stakeholders better visualize the strata, and be able to make a better decision regarding geotechnical works in the beginning phases of the project. Consequently, a LoD of 300 or LOMD level 3, is sufficient for the 3D model of the subsurface elements being modelled, which are the borehole and the subsurface layers in the case of this work (see fig. 21).

For the selection of the parameters which constitute the PDT for boreholes, it was explored different resources covering different phases of projects where geotechnical data would be needed, for subsurface geotechnical works (piles, anchors, excavation, etc.) and surface geotechnical works (foundations, retaining walls, etc.)(see fig. 32). It was also explored the needs of different users of geotechnical data like geotechnical engineers, designers, and any stakeholder who wants to understand about the subsurface layers of the project.

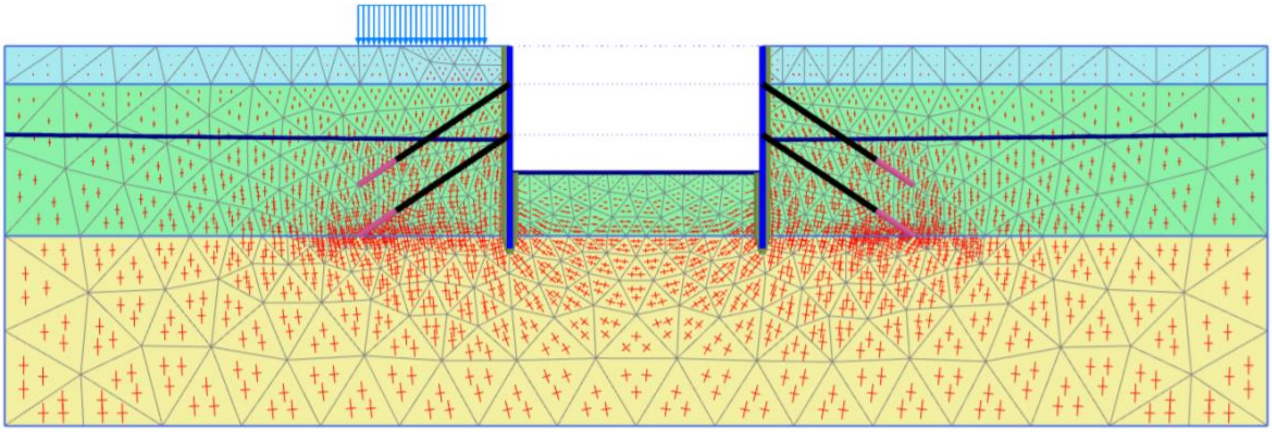


Figure 32: 2D representation of stresses on subsurface layers in the geotechnical design phase in Plaxis software (Plaxis 2018)

Three main pathways were taken into consideration for the collection of all the necessary data that should be included in the PDT. The first pathway is related to the design phase of a geotechnical engineering project and the geotechnical designers involved. The second pathway is related to the geotechnical investigation report produced for any project by the geotechnical research center by onsite and laboratory tests and analysis. The third pathway is from a review of the literature on what kind of geotechnical information is needed for geotechnical works and design as per expert advice.

The first pathway that was taken into consideration is to collect the necessary parameters used in the design of infrastructural elements and geotechnical works most commonly performed in projects like foundations, piles, and slope stabilization. It was looked into the manual design and calculation process of these elements, and parameters related to the subsurface that aided in the design process were collected. This step was taken to ensure that the basic information for manual calculations by designers are present and because these manual calculations are the basis of calculations done by software that does design and analysis of geotechnical elements. The parameters collected were defined in the following table (see table 4).

Table 4: Parameters needed for the manual design of geotechnical works

Geotechnical work		Piles	Slope stability	Foundations	Ground anchors
Reference		Gedeon, 2014	Deng, Zhao & Li, 2014	Szygielski, & Jeffrey, 2004 Handa, et al., 1984	Bachus, Pass, & Sabatini, 1999
Parameters needed for manual design and analysis	Friction angle	☑	☑	☑	☒
	Cohesion	☑	☑	☑	☒
	Unit weight (dry and wet)	☑	☑	☑	☑
	SPT N value	☒	☒	☑	☑
	Young's modulus	☑	☒	☒	☒
	Bulk weight density	☒	☒	☑	☒
	Moisture content	☒	☒	☒	☑
	Groundwater table	☒	☒	☒	☑
	Shear strength	☑	☒	☑	☑
	Compressive Strength	☒	☒	☑	☑
	consolidation	☒	☒	☒	☑
	PH & Chloride	☒	☒	☒	☑
	Atterberg limits	☒	☒	☒	☑

Then geotechnical design software requirements were explored, where the representation of earth layers requires certain data for the design process to be complete, and certain soil parameters must be inserted for the design and analysis of geotechnical elements like piles, foundation, retaining walls, etc. This source of information was considered to take into account the information that designers need in the phase of design. It was researched multiple online sources and manuals of different programs to get an insight into the needed parameters needed for design. The following table summarizes the findings and gives an idea of the variety of parameters needed for different geotechnical analysis tasks (see table 5).

Table 5: Parameters needed for the design of geotechnical works in different geotechnical software

Software		Plaxis	All Pile	Geo5	Peysanj
Vendor		Benteley	CivilTech	Fine	NovoTech
Parameters needed for design and analysis	Friction angle	☑	☑	☑	☑
	Cohesion	☑	☑	☑	☑
	Unit weight (dry and wet)	☑	☑	☑	☑
	SPT N value	☒	☑	☒	☒
	Young's modulus	☑	☑	☑	☑
	Poisson's ratio	☑	☑	☑	☑
	Angle of Dilation	☑	☒	☒	☒
	Groundwater table	☑	☑	☒	☑
	Shear strength	☑	☒	☒	☒
	H. & V. permeability	☑	☒	☒	☒
	Consolidation	☒	☒	☒	☑

The second pathway is related to the geotechnical investigation report produced for any project by the geotechnical research center. The information presenting this document will have, as a minimum, the project details, dates of drilling, Borehole location details and levels, drilling contractor and geologist details, drilling methods, sampling techniques, and depth intervals, In situ and laboratory test methods and results, material descriptions and boundaries, and groundwater depths. The level of detail of the information will vary to some extent between projects depending on the nature and purpose of the investigation, and/or proposed structure.

For the sake of collecting geotechnical parameters that should be included in the borehole PDT, it was explored two different sources: The geotechnical borehole logging guidelines of The Department of Transport and Main Roads in Queensland government (TMR 2016) and the logging guidelines

"*Engineer's quick reference guide for ground investigation*" that is written based on the British standards (see table 6) (RSK 2016). These are particularly important sources of information as the mentioned reports contain all the raw data collected from the site investigation and borehole drillings. The data collected was separated into three main categories: the general information part, soil and rock data, and in situ and laboratory tests.

Table 6: Set of British standards for the geotechnical report creation (RSK, 2016)

BS 5930:2015	Code of practice for ground investigation
BS 10175:2011	Investigation of potentially contaminated sites – Code of practice
-	UK Specification for Ground Investigation
BS EN 1997	Eurocode 7: Geotechnical design (part 1 and 2)
BS EN ISO 14688	Geotechnical investigation and testing – Identification and classification of soil (parts 1 and 2)
BS EN ISO 14689	Geotechnical investigation and testing – Identification and classification of rock (part 1)
BS EN ISO 22475	Geotechnical investigation and testing – Sampling methods and groundwater measurements (parts 1-3)
BS EN ISO 22476	Geotechnical investigation and testing – Field testing (parts 1-12)
BS EN ISO 22282	Geotechnical investigation and testing – Geohydraulic testing (parts 1-6)
BS 1377:1990	Methods of test for soils for civil engineering purposes (parts 1-9)
BS EN ISO 17892	Geotechnical investigation and testing – Laboratory testing of soil (multiple parts)

The general information part contains data related to the site as a whole, usually found in the geotechnical report document and the geotechnical data sheets, each borehole specific information, which is mainly found in the borehole drilling sheet, and the quantities of material used for that borehole (see fig. 24 & 25). This information should be enough to identify the project, client, contractor, drilling company, etc. It also should include specific information related to the borehole and total quantities used on the borehole, since usually, each borehole has a sheet defining it, this data should be included in the borehole object to be modelled. The following parameters were collected for the general information part:

- Project information: Project name, Project location, Project number, Job number, Drilling contractor, Client name, Main contractor.
- Borehole information: Start date, Finish date, Drill rig, Borehole diameter, Borehole project number, Borehole location easting, Borehole location northing, Borehole surface level, Groundwater level, Total borehole depth, Logged by, Reviewed By, From depth, To depth, Drilling method.

- Quantities: Casing diameter, Casing length, Drilling fluid, Water load volume, Consumed drill bits, Bentonite mud weight, polymer mud weight, core trays number.

The soil and rock data parts contain information about the soil or rock layer that describes them and identifies their characteristics. These descriptions are taken from a standardized methodology of describing soils and rock, figures 33 and 34 show how the description of some aspects of soil and rock is made.

Strength of Rock Material

(Based on Point Load Strength Index, corrected to 50mm diameter – $I_{s(50)}$. Field guide used if no tests available. Refer to AS 4133.4.1-2007.

Term	Symbol	Point Load Index (MPa) $I_{s(50)}$		Field Guide to Strength
Extremely Low	EL		≤0.03	Easily remoulded by hand to a material with soil properties.
Very Low	VL	>0.03	≤0.1	Material crumbles under firm blows with sharp end of pick; can be peeled with knife; too hard to cut a triaxial sample by hand. Pieces up to 3cm thick can be broken by finger pressure.
Low	L	>0.1	≤0.3	Easily scored with a knife; indentations 1mm to 3mm show in the specimen with firm blows of the pick point; has dull sound under hammer. A piece of core 150mm long by 50mm diameter may be broken by hand. Sharp edges of core may be friable and break during handling.
Medium	M	>0.3	≤1.0	Readily scored with a knife; a piece of core 150mm long by 50mm diameter can be broken by hand with difficulty.
High	H	>1	≤3	A piece of core 150mm long by 50mm diameter cannot be broken by hand but can be broken by a pick with a single firm blow; rock rings under hammer.
Very High	VH	>3	≤10	Hand specimen breaks with pick after more than one blow; rock rings under hammer.
Extremely High	EH	>10		Specimen requires many blows with geological pick to break through intact material; rock rings under hammer.

Notes:

1. These terms refer to the strength of the rock material and not to the strength of the rock mass which may be considerably weaker due to the effect of rock defects.
2. Anisotropy of rock material samples may affect the field assessment of strength.

Figure 33: Strength condition identification legend (TMR, 2016)

Consistency - Essentially Cohesive Soils

Term	Field Guide	Symbol	SPT "N" Value	Undrained Shear Strength s_u (kPa)	Unconfined Compressive Strength q_u (kPa)
Very soft	Oozes between fingers when squeezed in hand.	VS	0-2	<12	<25
Soft	Easily moulded with fingers.	S	2-4	12-25	25-50
Firm	Can be moulded by strong pressure of fingers.	F	4-8	25-50	50-100
Stiff	Not possible to mould with fingers.	St	8-15	50-100	100-200
Very stiff		VSt	15-30	100-200	200-400
Hard	Can be indented with difficulty by thumb nail.	H	>30	>200	>400

Figure 34: Consistency of cohesive soils identification legend (TMR, 2016)

- For the identification of rocks the following parameters were identified:

  Rock type, Color, Total core recovery, Solid core recovery, Rock quality designation, Weathering, Strength, Discontinuity description, Discontinuity spacing, Structure, Texture, Fabric, Grain size, Secondary minerals, Distinctive features, Discontinuity angle of incidence, Discontinuity frequency, and Additional remarks.

- For the identification of soils the following parameters were identified:

  Soil type, Color, Moisture, Consistency of cohesive soils, Consistency of non-cohesive soils, Grain size, Odour, Angularity, Bedding, Relative density, Strength, Discontinuities, Plasticity, Sorting or grading, organic content, secondary minerals, Peat description, and Additional remarks.

The in-situ and laboratory tests part has all the results that were measured on-site or in the laboratory. The laboratory tests are divided into different categories: compaction, strength, classification, and other tests. The laboratory and in-situ tests performed results in the deduction of various soil parameters. It was collected all these parameters to be added to the PDT. The parameters identified are as follows:

- Laboratory classification test's results parameters: Moisture content, Liquid limit, Plastic limit, Bulk weight density, Unit weight of soil (wet and dry), and Specific gravity.
- Laboratory compaction test's results parameters: California Bearing ratio, Maximum dry density, and Optimum moisture content.
- Laboratory strength test's results parameters: Cohesion (drained and undrained), Angle of internal friction (drained and undrained), Angle of dilation, Shear strength, Tensile strength, Compressive Strength, Poisson's ratio, and Modulus of elasticity (young's modulus; drained and undrained).
- Laboratory other test's results parameters: Coefficient of volume compressibility, Coefficient of consolidation, Porosity, PH value, Sulphate content, and Permeability (horizontal and vertical direction).
- Insitu Test's results parameters: Standard Penetration Test, Soakaway test, Percolation test, Mackintosh probes, Hand vane, Pocket penetrometer, Schmidt hammer, Inclinometer, Extensometer, Piezometer.

For the third pathway, which is a review of the literature on what kind of geotechnical information is needed for geotechnical works and design as per expert advice, it was collected some information from surveys made with geotechnical engineers. These surveys explored what are the parameters that geotechnical engineers would think useful to include in the BIM model. The outcome of the surveys was that the respondents considered the essential data for inclusion in the BIM process are the soil strength parameters (e.g. angle of internal friction, cohesion; 37%), the bearing capacity characteristics of soil (e.g. bearing resistance, CBR; 33%), and the soil stratigraphy (29%) (see fig. 35)(Tawelian, & Mickovski, 2016).

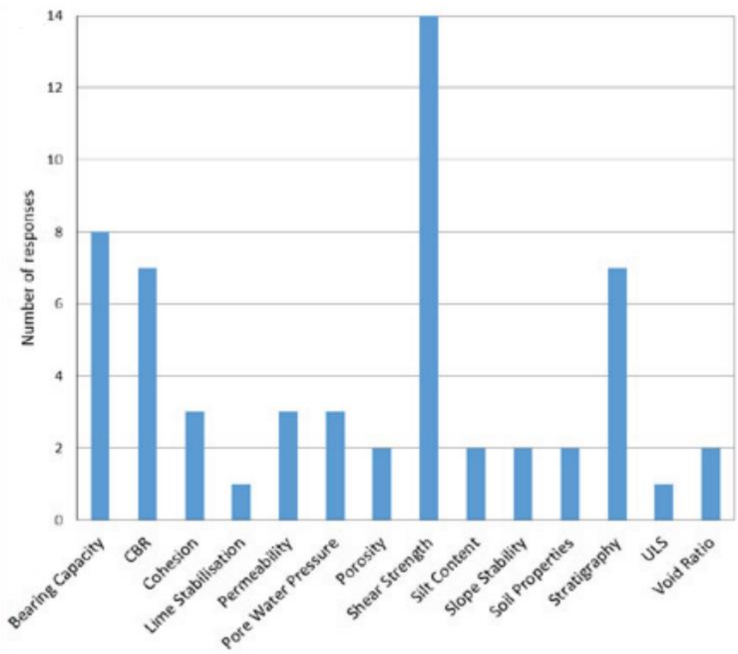


Figure 35: Geotechnical data considered essential for inclusion in the BIM model (Tawelian, et al., 2016)

3.2 PDT proposal

The three pathways resulted in a large number of parameters that were compared, analyzed, and segregated so that no repetition of parameters is made, as some parameters can have different namings but are meant to represent the same parameter depending on the source. The final list of parameters was separated in the PDT under five different categories, where the data that is of the same nature or serve the same purpose were put under the same title. The PDT has a metadata part as well that defines it and describes its general purpose.

The first category in the proposed PDT is titled “Borehole general information” (see fig. 36) and it contains 28 Parameters. Part of these parameters is for the general definition of the project information. This information is important to identify who asked for this data to be extracted, and where is the location of this project and which companies were involved in the process. This will make it easier for identifying the key stakeholders involved with this borehole in the future, for whatever purpose.

The other part of the parameters is about the borehole information so that it is possible to identify who monitored the logging and reviewing of the data, what are the exact coordinates and level of this borehole when was it started and completed, how much material was used for the drilling, and what are the total depths performed in this borehole.

Borehole Master PDT			
Template Category	Geotechnical Data	Category Description	Borehole Data
Template Version	1.0	Suitability for Use	Geotechnical design software - BIM integration of data
General Information			
ProjectName		BoreholeProjectNumber	
ProjectLocation		TotalBoreholeDepth	
ProjectNumber		StartDate	
MainContractor		FinishDate	
ClientName		DrillRig	
DrillingContractor		LoggedBy	
JobNumber		ReviewedBy	
Parameter Name	**Value**	**Unit**	**Notes**
BoreholeDiameter		mm	(mandatory field)
BoreholeLocationX		Number	(mandatory field)
BoreholeLocationY		Number	(mandatory field)
BoreholeSurfaceLevel		Number	(mandatory field)
GroundWaterLevelFromTop		Number	
CasingDiameter		mm	
CasingLength		m	
DrillingFluid		Text	
WaterLoadVolume		Litre	
ConsumedDrillBits		Number	
BentoniteMudWeight		Kg	
PolymerMudWeight		Litre	
CoreTraysNumber		Number	
DrillingMethod		Text	

Figure 36: Borehole PDT metadata and general information category

The second and third categories in the PDT are titled “Rock Layer Data” and “Soil Layer Data” (see fig. 37). These two categories contain 20 parameters each and are mainly derived from the geotechnical investigation report from the in-situ readings collected during the extraction of the borehole materials. The geologist or engineer present on-site usually analyzes the samples retrieved from the borehole and fills a sheet for the detailed description of the soil’s characteristics and condition at the moment of extraction with descriptions like the moisture condition of the sample, odor, texture, consistency and so on, based on the standard method of soil description. These two categories are the parts that a user would multiply and rearrange in the Borehole PDT to represent all the layers that are found in the borehole under study.

Rock Layer Data			
Parameter Name	**Value**	**Unit**	**Notes**
LayerNumber		Number	(mandatory field)
RockType		Text	Sandstone, Mudstone, Limestone … (mandatory field)
FromDepth		m	(mandatory field)
ToDepth		m	(mandatory field)
RockColor		Text	(Lightness, Chroma, Hue): Light Reddish Brown
RockWeatheringCondition		Text	Unweathered
RockStrengthCondition		Text	Weak, medium strong, strong …
RockDiscontinuityDescription		Text	Roughness, aperture, infilling, Termination type, seepag
RockDiscontinuitySpacing		Text	Wide, medium, close …
RockDiscontinuityAngleOfIncidenc		Degree	Relative to the horizontal
RockDiscontinuityFrequency		No./m	Number per metre of core
RockStructure		Text	Nature of individual grains
RockFabric		Text	The arrangement (or preferred orientation) of the grains
RockGrainSize		Text	Fine, medium, coarse …
RockSecondaryMinerals		Text	Silicification, albitisation, pyrite …
RockDestinctiveFeatures		Text	Discoloration, pervasive staining or other notable features
RockTotalCoreRecovery		%	[Sample depth,result]; [Sample depth, result]
RockSolidCoreRecovery		%	[Sample depth,result]; [Sample depth, result]
RockQualityDesignation		%	[Sample depth,result]; [Sample depth, result]
RockAdditionalRemarks		Text	
Soil Layer Data			
Parameter Name	**Value**	**Unit**	**Notes**
LayerNumber		Number	(mandatory field)
FromDepth		m	(mandatory field)
ToDepth		m	(mandatory field)
SoilType		Text	Clayey sand, silty sand … (mandatory field)
SoilColor		Text	(Lightness, Chroma, Hue): Light Reddish Brown
SoilMoistureCondition		Text	Dry, moist or wet
SoilConsistencyCohesive		Text	Very soft, soft, firm, stiff, very stiff, hard
SoilGrainSize		Text	mm or boulders to clay defintions
SoilConsistencyNonCohesive		Text	Very loose, loose, medium dense, dense, very dense
SoilOdour		Text	Camphor, Musk, Floral, Vinegar …
SoilAngularity		Text	For course soil: Angular, Subrounded, Rounded …
SoilPeatDescription		Text	For organic soil: condition, constituents, decomposition …
SoilRelativeDensity		%	Density index
SoilPlasticity		Text	Low plasticity, intermediate plasticity, high plasticity …
SoilGrading		Text	Well graded, poorly graded …
SoilDiscontinuities		Text	Wide, medium, close; fissures, shears …
SoilOrganicContent		Text	Slightly organic, organic, very organic
SoilSecondaryMinerals		Text	Shelly, calcareous …
SoilBeddingDescription		Text	Very thickly, thickly, medium, thinly …
SoilAdditionalRemarks		Text	Zoning, defects, cementation

Figure 37: Rock description and soil description categories in the borehole PDT

The fourth category is named “Laboratory test results” and is divided into four sub-categories. The first sub-category is titled “Classification laboratory test results” and it has 7 parameters for the results of laboratory tests that would help classify the soil’s physical characteristics like moisture content, plastic and liquid limits, unit weight, and so on. The second sub-category is titled

"Compaction laboratory test results", it has 3 parameters related to compaction characteristics of the soil (see fig. 38).

The third sub-category is titled "Strength laboratory test results" and it contains 11 parameters (see fig. 38) that identify the strength characteristics of the soil. Parameters in this category include cohesion, angle of internal friction, modulus of elasticity, compressive strength, shear strength, and a few more. This category has great importance as these parameters are essential for the design of geotechnical elements and they appear in most resources that were researched and talked about in part 3.1.

Laboratory Test Results			
Parameter Name	**Value**	**Unit**	**Notes**
Classification lab test results			
MoistureContent		%	[Sample depth,result]; [Sample depth, result]
LiquidLimit		%	[Sample depth,result]; [Sample depth, result]
PlasticLimit		%	[Sample depth,result]; [Sample depth, result]
BulkWeightDensity		KN/m3	[Sample depth,result]; [Sample depth, result]
UnitWeightOfWetSoil		KN/m3	[Sample depth,result]; [Sample depth, result]
UnitWeightOfDrySoil		KN/m3	[Sample depth,result]; [Sample depth, result]
SpecificGravity		number	[Sample depth,result]; [Sample depth, result]
Compaction lab test results			
CaliforniaBearingRatio		%	
MaximumDryDensity		Kg/m3	
OptimumMoistureContent		%	
Strength laboratory test results			
CohesionUndrained		Kpa	[Sample depth,result]; [Sample depth, result]
CohesionDrained		Kpa	[Sample depth,result]; [Sample depth, result]
AngleOfInternalFrictionUndrained		degree	[Sample depth,result]; [Sample depth, result]
AngleOfInternalFrictionDrained		degree	[Sample depth,result]; [Sample depth, result]
AngleOfDilation		degree	[Sample depth,result]; [Sample depth, result]
ModulusOfElasticityUndrained		Mpa	[Sample depth,result]; [Sample depth, result]
ModulusOfElasticityDrained		Mpa	[Sample depth,result]; [Sample depth, result]
CompressiveStrength		Mpa	[Sample depth,result]; [Sample depth, result]
Shear Strength		Kpa	[Sample depth,result]; [Sample depth, result]
TensileStrength		KN/m2	[Sample depth,result]; [Sample depth, result]
PoissonsRatio		number	[Sample depth,result]; [Sample depth, result]

Figure 38: Classification, compaction, and Strength laboratory test results categories in the borehole PDT

The fourth sub-category is titled "Other laboratory test results" and it has 8 parameters. This category is for any other laboratory tests that do not fit in the previous categories like chemical and oedometer tests. Finally, the fifth category in the PDT is reserved for all the tests that are done on-site and it is titled "In-Situ Test Results". This category contains tests like SPT, which is a very important parameter for soil classification and many other parameters can be derived from it by correlation, percolation testing, hand vane, and so on (see fig. 39).

Other laboratory test results			
CoefficientOfVolumeCompressibilit		cm2/kg	[Sample depth,result]; [Sample depth, result]
CoefficientOfConsolidation		m2/min	[Sample depth,result]; [Sample depth, result]
Porosity		%	[Sample depth,result]; [Sample depth, result]
PHValue		number	[Sample depth,result]; [Sample depth, result]
ChlorideContent		%	[Sample depth,result]; [Sample depth, result]
SulphateContent		%	SO3/SO4: [Sample depth,result]; [Sample depth, result]
PermeabilityHorizontalDirection		m/day	[Sample depth,result]; [Sample depth, result]
PermeabilityVerticalDirection		m/day	[Sample depth,result]; [Sample depth, result]
In-Situ Test Results			
Parameter Name	Value	Unit	Notes
SPTNValue		Number	[Sample depth,result]; [Sample depth, result]
SPTCorrectedNValue		Number	[Sample depth,result]; [Sample depth, result]
SoakawayTesting		mm/hr	Soil infiltraion rate
PercolationTesting		ml/min	
MackintoshProbes		blows.mm	
HandVane		Kpa	
PocketPenetrometer		Kpa	
SchmidtHammer		R	Average rebound index
InclinometerInstalled		Yes/No	
ExtensometerInstalled		Yes/No	
PiezometerInstalled		Yes/No	

Figure 39: Other lab test results and In-situ test results categories in the borehole PDT

To demonstrate how a borehole PDT would look like, it was assumed an example where a borehole has a soil, rock, and another soil layer consecutively. The user creating a PDT for this borehole would start by creating a new file in their computer that would contain all the PDTs for all the boreholes they have in the project. Then the user would copy the PDT from the Master Template provided to create a PDT for each borehole.

For the aforementioned borehole for example the user would start by adding the general information category. After that, the user would copy the "Soil Layer Data" category from the master template provided and put it after the General Information part, and it would represent layer one. Then, the user would copy the "Rock Layer Data" category and insert it after the "Soil Layer Data" and it would represent layer two. After that, the user would add another "Soil Layer Data" part to represent the third layer. Following the layers of soil and rock, the user would add the "Laboratory Test Results" and "In-Situ Test Results" categories to finalize the borehole PDT (see fig. 40).

General Information			
ProjectName		BoreholeProjectNumber	
ProjectLocation		TotalBoreholeDepth	
ProjectNumber		StartDate	
MainContractor		FinishDate	
ClientName		DrillRig	
DrillingContractor		LoggedBy	
JobNumber		ReviewedBy	
Parameter Name	**Value**	**Unit**	**Notes**
BoreholeDiameter		mm	(mandatory field)
BoreholeLocationX		Number	(mandatory field)
BoreholeLocationY		Number	(mandatory field)
BoreholeSurfaceLevel		Number	(mandatory field)
GroundWaterLevelFromTop		Number	
CasingDiameter		mm	
CasingLength		m	
DrillingFluid		Text	
WaterLoadVolume		Litre	
ConsumedDrillBits		Number	
BentoniteMudWeight		Kg	
PolymerMudWeight		Litre	
CoreTraysNumber		Number	
DrillingMethod		Text	
Soil Layer Data			
Parameter Name	**Value**	**Unit**	**Notes**
LayerNumber		Number	(mandatory field)
FromDepth		m	(mandatory field)
ToDepth		m	(mandatory field)
SoilType		Text	Clayey sand, silty sand... (mandatory field)
SoilColor		Text	(Lightness, Chroma, Hue): Light Reddish Brown
SoilMoistureCondition		Text	Dry, moist or wet
SoilConsistencyCohesive		Text	Very soft, soft, firm, stiff, very stiff, hard
SoilGrainSize		Text	mm or boulders to clay definitions
SoilConsistencyNonCohesive		Text	Very loose, loose, medium dense, dense, very dense
SoilOdour		Text	Camphor, Musk, Floral, Vinegar...
SoilAngularity		Text	For course soil: Angular, Subrounded, Rounded...
SoilPeatDescription		Text	For organic soil: condition, constituents, decomposition
SoilRelativeDensity		%	Density index
SoilPlasticity		Text	Low plasticity, intermediate plasticity, high plasticity...
SoilGrading		Text	Well graded, poorly graded...
SoilDiscontinuities		Text	Wide, medium, close; fissures, shears ...
SoilOrganicContent		Text	Slightly organic, organic, very organic
SoilSecondaryMinerals		Text	Shelly, calcareous...
SoilBeddingDescription		Text	Very thickly, thickly, medium, thinly...
SoilAdditionalRemarks		Text	Zoning, defects, cementation
Rock Layer Data			
Parameter Name	**Value**	**Unit**	**Notes**
LayerNumber		Number	(mandatory field)
RockType		Text	Sandstone, Mudstone, Limestone... (mandatory field)
FromDepth		m	(mandatory field)
ToDepth		m	(mandatory field)
RockColor		Text	(Lightness, Chroma, Hue): Light Reddish Brown
RockWeatheringCondition		Text	Unweathered
RockStrengthCondition		Text	Weak, medium strong, strong...
RockDiscontinuityDescription		Text	Roughness, aperture, infilling, Termination type, seepa
RockDiscontinuitySpacing		Text	Wide, medium, close...
RockDiscontinuityAngleOfIncidence		Degree	Relative to the horizontal
RockDiscontinuityFrequency		No./m	Number per metre of core
RockStructure		Text	Nature of individual grains
RockFabric		Text	The arrangement (or preferred orientation) of the grai
RockGrainSize		Text	Fine, medium, coarse...
RockSecondaryMinerals		Text	Silicification, albitisation, pyrite...
RockDestinctiveFeatures		Text	Discoloration, pervasive staining or other notable featu
RockTotalCoreRecovery		%	[Sample depth,result]; [Sample depth, result]
RockSolidCoreRecovery		%	[Sample depth,result]; [Sample depth, result]
RockQualityDesignation		%	[Sample depth,result]; [Sample depth, result]
RockAdditionalRemarks		Text	
Soil Layer Data			
Parameter Name	**Value**	**Unit**	**Notes**
LayerNumber		Number	(mandatory field)
FromDepth		m	(mandatory field)
ToDepth		m	(mandatory field)

Figure 40: Example of categories distribution for a borehole with layers: Soil, Rock, and Soil consecutively

To ensure that important data is recorded correctly in the PDT, a validation rule was created with basis on some data input cells. Borehole coordinates and levels for example are very important for modelling and hence a validation rule was created to ensure they are written in the correct format. Also, the layers depths and main classification of soil and rock layers are crucial data, hence validation rules were also created to ensure that these data are recorded correctly or not left blank (see fig. 41).

A warning note was also added to notify the user on filling important soil or rock parameters (see fig. 41). To identify the most important parameters that should be added to a borehole, the geotechnical investigation report and the parameters necessary for design mentioned previously were revised and the following parameters were chosen to have a rule that warns the user that these parameters are important for the borehole PDT:

SPTNValue, SPTCorrectedNValue, CompressiveStrength, TensileStrength, PoissonsRatio, ModulusOfElasticityUndrained, AngleOfInternalFrictionUndrained, CohesionUndrained, UnitWeightOfWetSoil, BulkWeightDensity

However, a validation rule that would not allow the user to complete the PDT was not added, hence the user can complete the PDT even without these parameters, in case the data was not available for whatever purpose. The absence of these data will affect the quality of the PDT, but gives the user the chance to add whatever data available. It will not affect the modelling of boreholes and subsurface layers, which was not the case with the coordinates and dimensions data, as they were cruetial and the modelling of boreholes and subsurface layers is impossible without them.

After the PDT is completed by the user for a single borehole, where its name becomes Product Data Sheet, the user can save in the project file and move on to complete the Product Data Sheets for all the other boreholes and save all the sheets of the same project in a single file for processing later on.

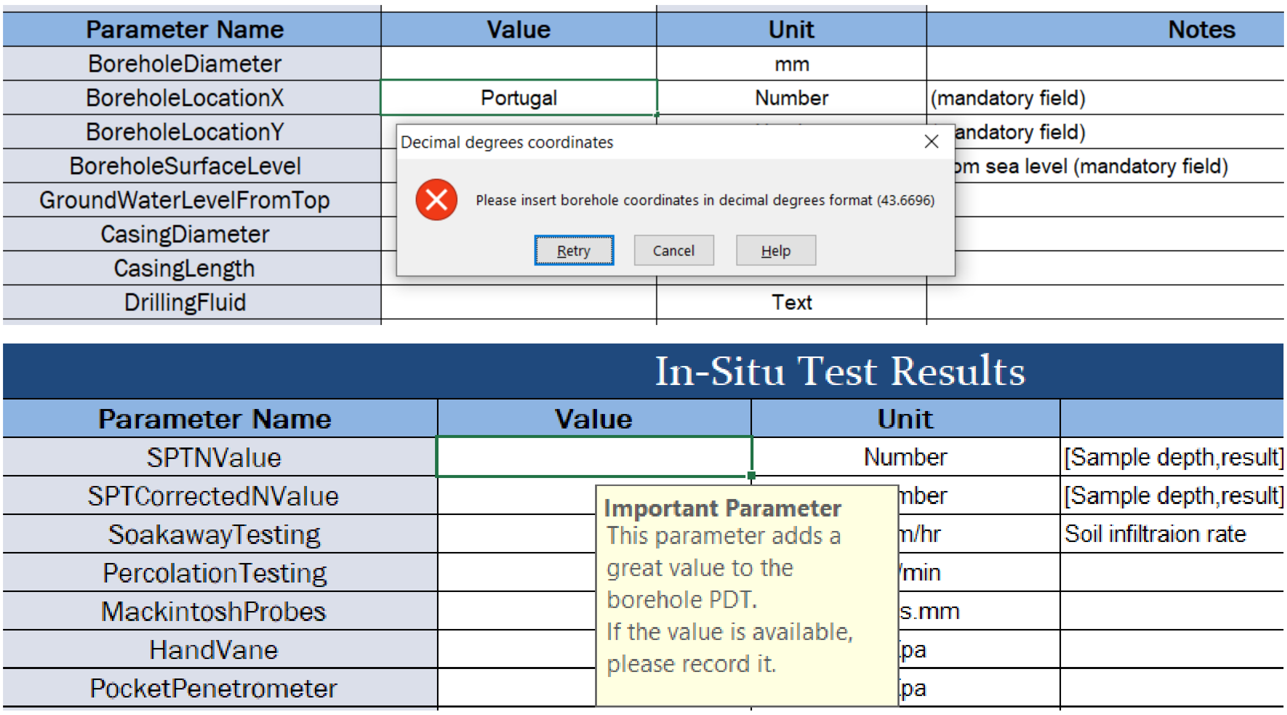


Figure 41: Validation rule for coordinates of borehole and warning rule for important parameters

The PDT proposed serves as a form to standardize the way geotechnical information is preserved. It is a digital-based BIM sharable form that has all the necessary information needed from boreholes. It is important to note that since this document is digital and can be used to extract information and geotechnical data, it is important that the parameters written in the PDT conform with the BIM object standards set out for BIM objects and that the naming of parameters follows the standards naming conventions.

This consideration is not only for standardizing the way the parameters are written but also these guidelines help in preventing errors when using the data in formulae when extracted digitally from the PDT for whatever reason. For that purpose, the OBOS Open BIM Object Standard (NATSPEK, 2018) and NBS BIM Object Standard (NBS, 2019) documents were revised. Some of the guidelines that were considered following the naming conventions are:

- Names and naming fields shall include only the following characters:
  - Uppercase letters (A to Z) from the ISO basic Latin alphabet.
  - Lowercase letters (a to z) from the ISO basic Latin alphabet.
  - Numbers (0 to 9).
  - Underscore (_), used only to separate the file name from the file extension.
- Names and naming fields shall not include any of the following characters:
  - Symbols or mathematical operators, including, but not limited to, (! @ # $ % ^ & * { } ' ? > " , < / ~), and spaces.
  - The use of hyphen character should be avoided as it can cause errors when the name (or property) is used within formulae, due to the hyphen also representing the mathematical subtraction operator.
- PascalCase shall be used to join separate words within naming fields and for the naming of properties.

Following the guidelines of the same standards, the borehole parameter's units were all to be recorded in metric and following the *Système international d'unités* (SI) protocols for dimensions and units generally. The standards state that "*metric geometry in millimeters shall be used unless specified otherwise by local requirements or if the scale of the object being modelled would better suit meters or kilometers*". Since dealing with dimensions related to earthworks, which is usually related to big scale objects, the use of meters for the dimensions in the PDT was preferred.

The three pathways taken as resources to collect all the possible parameters that can be included in the borehole PDT yielded 104 parameters in total. All these parameters included in the PDT are supposed to be of relevance to the different stakeholders involved in the different phases of the lifecycle of an infrastructural project (see fig. 42).

Borehole Master PDT			
Template Category	Geotechnical Data	Category Description	Borehole Data
Template Version	1.0	Suitability for Use	Geotechnical design software - BIM integration of data
General Information			
ProjectName		BoreholeProjectNumber	
ProjectLocation		TotalBoreholeDepth	
ProjectNumber		StartDate	
MainContractor		FinishDate	
ClientName		DrillRig	
DrillingContractor		LoggedBy	
JobNumber		ReviewedBy	
Parameter Name	**Value**	**Unit**	**Notes**
BoreholeDiameter		mm	(mandatory field)
BoreholeLocationX		Number	(mandatory field)
BoreholeLocationY		Number	(mandatory field)
BoreholeSurfaceLevel		Number	(mandatory field)
GroundWaterLevelFromTop		Number	
CasingDiameter		mm	
CasingLength		m	
DrillingFluid		Text	
WaterLoadVolume		Liter	
ConsumedDrillBits		Number	
BentoniteMudWeight		Kg	
PolymerMudWeight		Litre	
CoreTraysNumber		Number	
DrillingMethod		Text	
Rock Layer Data			
Parameter Name	**Value**	**Unit**	**Notes**
LayerNumber		Number	(mandatory field)
RockType		Text	Sandstone, Mudstone, Limestone ... (mandatory field)
FromDepth		m	(mandatory field)
ToDepth		m	(mandatory field)
RockColor		Text	(Lightness, Chroma, Hue): Light Reddish Brown
RockWeatheringCondition		Text	Unweathered
RockStrengthCondition		Text	Weak, medium strong, strong ...
RockDiscontinuityDescription		Text	Roughness, aperture, infilling, Termination type, seepage
RockDiscontinuitySpacing		Text	Wide, medium, close ...
RockDiscontinuityAngleOfIncidence		Degree	Relative to the horizontal
RockDiscontinuityFrequency		No./m	Number per metre of core
RockStructure		Text	Nature of individual grains
RockFabric		Text	The arrangement (or preferred orientation) of the grains
RockGrainSize		Text	Fine, medium, coarse ...
RockSecondaryMinerals		Text	Silicification, albitisation, pyrite ...
RockDestinctiveFeatures		Text	Discoloration, pervasive staining or other notable features
RockTotalCoreRecovery		%	[Sample depth,result]; [Sample depth, result]
RockSolidCoreRecovery		%	[Sample depth,result]; [Sample depth, result]
RockQualityDesignation		%	[Sample depth,result]; [Sample depth, result]
RockAdditionalRemarks		Text	
Soil Layer Data			
Parameter Name	**Value**	**Unit**	**Notes**
LayerNumber		Number	(mandatory field)
FromDepth		m	(mandatory field)
ToDepth		m	(mandatory field)
SoilType		Text	Clayey sand, silty sand ... (mandatory field)
SoilColor		Text	(Lightness, Chroma, Hue): Light Reddish Brown
SoilMoistureCondition		Text	Dry, moist or wet
SoilConsistencyCohesive		Text	Very soft, soft, firm, stiff, very stiff, hard
SoilGrainSize		Text	mm or boulders to clay defintions
SoilConsistencyNonCohesive		Text	Very loose, loose, medium dense, dense, very dense
SoilOdour		Text	Camphor, Musk, Floral, Vinegar ...
SoilAngularity		Text	For course soil: Angular, Subrounded, Rounded ...
SoilPeatDescription		Text	For organic soil: condition, constituents, decomposition ...
SoilRelativeDensity		%	Density index
SoilPlasticity		Text	Low plasticity, intermediate plasticity, high plasticity ...
SoilGrading		Text	Well graded, poorly graded ...
SoilDiscontinuities		Text	Wide, medium, close; fissures, shears ...
SoilOrganicContent		Text	Slightly organic, organic, very organic
SoilSecondaryMinerals		Text	Shelly, calcareous ...
SoilBeddingDescription		Text	Very thickly, thickly, medium, thinly ...
SoilAdditionalRemarks		Text	Zoning, defects, cementation

Laboratory Test Results			
Parameter Name	**Value**	**Unit**	**Notes**
Classification lab test results			
MoistureContent		%	[Sample depth,result]; [Sample depth, result]
LiquidLimit		%	[Sample depth,result]; [Sample depth, result]
PlasticLimit		%	[Sample depth,result]; [Sample depth, result]
BulkWeightDensity		KN/m3	[Sample depth,result]; [Sample depth, result]
UnitWeightOfWetSoil		KN/m3	[Sample depth,result]; [Sample depth, result]
UnitWeightOfDrySoil		KN/m3	[Sample depth,result]; [Sample depth, result]
SpecificGravity		number	[Sample depth,result]; [Sample depth, result]
Compaction lab test results			
CaliforniaBearingRatio		%	[Sample depth,result]; [Sample depth, result]
MaximumDryDensity		Kg/m3	[Sample depth,result]; [Sample depth, result]
OptimumMoistureContent		%	[Sample depth,result]; [Sample depth, result]
Strength laboratory test results			
CohesionUndrained		Kpa	[Sample depth,result]; [Sample depth, result]
CohesionDrained		Kpa	[Sample depth,result]; [Sample depth, result]
AngleOfInternalFrictionUndrained		degree	[Sample depth,result]; [Sample depth, result]
AngleOfInternalFrictionDrained		degree	[Sample depth,result]; [Sample depth, result]
AngleOfDilation		degree	[Sample depth,result]; [Sample depth, result]
ModulusOfElasticityUndrained		Mpa	[Sample depth,result]; [Sample depth, result]
ModulusOfElasticityDrained		Mpa	[Sample depth,result]; [Sample depth, result]
BearingCapacity		Kpa	[Sample depth,result]; [Sample depth, result]
Shear Strength		Kpa	[Sample depth,result]; [Sample depth, result]
TensileStrength		KN/m2	[Sample depth,result]; [Sample depth, result]
PoissonsRatio		number	[Sample depth,result]; [Sample depth, result]
Other laboratory test results			
CoefficientOfVolumeCompressibility		cm2/kg	[Sample depth,result]; [Sample depth, result]
CoefficientOfConsolidation		m2/min	[Sample depth,result]; [Sample depth, result]
Porosity		%	[Sample depth,result]; [Sample depth, result]
PHValue		number	[Sample depth,result]; [Sample depth, result]
ChlorideContent		%	[Sample depth,result]; [Sample depth, result]
SulphateContent		%	SO3/SO4: [Sample depth,result]; [Sample depth, result]
PermeabilityHorizontalDirection		m/day	[Sample depth,result]; [Sample depth, result]
PermeabilityVerticalDirection		m/day	[Sample depth,result]; [Sample depth, result]

In-Situ Test Results			
Parameter Name	**Value**	**Unit**	**Notes**
SPTNValue		Number	[Sample depth,result]; [Sample depth, result]
SPTCorrectedNValue		Number	[Sample depth,result]; [Sample depth, result]
SoakawayTesting		mm/hr	Soil infiltraion rate
PercolationTesting		ml/min	
MackintoshProbes		blows.mm	
HandVane		Kpa	
PocketPenetrometer		Kpa	
SchmidtHammer		R	Average rebound index
InclinometerInstalled		Yes/No	
ExtensometerInstalled		Yes/No	
PiezometerInstalled		Yes/No	

Figure 42: Borehole Master PDT

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4 VISUAL PROGRAMMING FOR MODELLING BOREHOLES AND SUBSURFACE LAYERS

The main objective of using visual programming in this work is to create an algorithm that would help in the better use of geotechnical data. Dynamo is the platform used in this work. The choice of this program was made because Dynamo is a part of a BIM platform, which is Revit, and the goal was to create a program within the BIM software to handle the geotechnical data. Consequently, the user's need to use an external source that deals with geotechnical data, for modelling boreholes and subsurface layers and managing borehole data, would decrease. This means that the transfer of data between software and the BIM platform would not be necessary, and this would decrease the risk of data loss.

To obtain the results intended by this work, four phases were identified to complete the work. The first phase is to extract all the geotechnical data available in the PDT into Dynamo and the BIM platform to manage this data, preserve it, and use it to model the geotechnical elements. Phase two of the work is to use the geotechnical data extracted to model the boreholes as 3D objects in the BIM platform and attach all the parameters in the PDT to the created boreholes. The third phase is to use the geotechnical data to model the subsurface layers in 3D and attach the basic parameters that define the material of these layers from the PDT. The final phase is to export the model and data in an open-source format, which is the IFC, for interoperability and long term preservation of data.

4.1 Borehole datasheet and borehole object creation

4.1.1 Borehole datasheet

To use geotechnical data efficiently in the visual coding software, it is important to organize the way the information is extracted to be able to use it without complications in the program. For that purpose, an excel sheet containing all the parameters mentioned earlier in the proposed PDT was created. The sheet is organized in a way that it is possible to insert multiple borehole information in one single form for a single project or location. This sheet, which is representing the master borehole PDT is the starting point of the geotechnical data journey as per the BIM approach. It is important to note that a correlation between the PDT created for users and the borehole excel sheet which is created for programming purposes can be made relatively easily and quickly, however it was not explored here and it is a matter left for future development.

The data entry part of the work which requires manual input of data is not an additional step that is added to the general geotechnical data journey, but just another form of input. The common practice is that this data is usually inserted manually in geotechnical software, like gINT from Bentley (see fig. 43), that takes borehole data as input and produces report sheets, graphs, and 2D sections of boreholes. These reports then are included in the geotechnical investigation report. Hence the manual input of data will always be a part of the process, but it can become more efficient in the future.

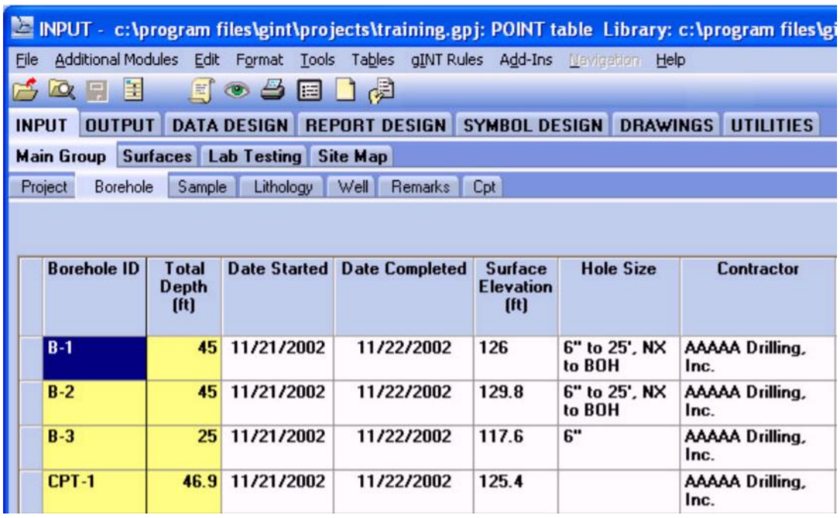


Figure 43: Data entry page for boreholes in geotechnical software gINT (Benteley 2020)

The sheet created had to take into consideration that a project can have a small or large number of boreholes and that the user can insert different data for different layers in the same borehole (see fig. 44). Hence it was designed in a way that the user would insert additional rows to represent the number of subsurface layers. For example, assuming that the borehole has 7 different layers, then the same borehole in the sheet would have 7 different rows representing them as seen in figure 44.

The number of parameters in the sheet is the same as the proposed PDT since this sheet is just another form or arrangement of the PDT parameters where multiple boreholes can be introduced in one sheet. It is important to note that the parameter’s names in the sheet were the same as the PDT, and it also follows the standard convention of naming BIM objects. This is important as later on these parameter names will be used to extract data from the sheet, so any difference would cause an error in extracting the data, hence, the names of the parameters were also written in PascalCase.

	A	B	C	D	E	F	G	H	I	J
1	BHNumber	Easting	Northing	BHLevel	DepthTop	DepthBase	LayerNumber	ProjectName	ProjectLocation	ProjectNumber
2	1	0	0	0	0	-10	1	n/a	n/a	n/a
3	1	0	0	0	-10	-20	2	n/a	n/a	n/a
4	1	0	0	0	-20	-30	3	n/a	n/a	n/a
5	1	0	0	0	-30	-35	4	n/a	n/a	n/a
6	2	100	100	3	0	-10	1	n/a	n/a	n/a
7	2	100	100	3	-10	-15	2	n/a	n/a	n/a
8	2	100	100	3	-15	-30	3	n/a	n/a	n/a
9	2	100	100	3	-30	-35	4	n/a	n/a	n/a
10	3	0	100	5	0	-10	1	n/a	n/a	n/a
11	3	0	100	5	-10	-15	2	n/a	n/a	n/a
12	3	0	100	5	-15	-30	3	n/a	n/a	n/a
13	3	0	100	5	-30	-35	4	n/a	n/a	n/a
14	4	100	0	2	0	-10	1	n/a	n/a	n/a
15	4	100	0	2	-10	-20	2	n/a	n/a	n/a
16	4	100	0	2	-20	-30	3	n/a	n/a	n/a
17	4	100	0	2	-30	-35	4	n/a	n/a	n/a
18	5	25	25	6	0	-5	1	n/a	n/a	n/a
19	5	25	25	6	-5	-15	2	n/a	n/a	n/a
20	5	25	25	6	-15	-25	3	n/a	n/a	n/a
21	5	25	25	6	-25	-30	4	n/a	n/a	n/a
22	6	25	75	2	0	-10	1	n/a	n/a	n/a

Figure 44: Part of borehole datasheet created for borehole

The primary purpose of the created excel sheet is to extract data and use it to model boreholes as objects in the BIM platform, however, it also had another purpose which is to help manage and rearrange data to be able to model the subsurface layers in 3D. Hence it was created another page in the sheet in the same excel file to address this issue (see fig. 45).

The second page was created after trying to model the subsurface layers in 3D with the visual scripting tool using the first sheet and it created problems in processing the data, and it was found more efficient if the data was arranged as needed in the excel sheet before extracting the data into the scripting tool.

The purpose of the second sheet was to arrange the location data of subsurface layers with the same material from different boreholes together and in order, so that when the data is pulled into the scripting program, it was easier to use and without errors. This issue will be discussed further in the upcoming chapter.

	A	B	C	D	E	F	G	H	I	J
1	BHNumber	Easting	Northing	BHLevel	DepthTop	DepthBase	LayerNumb	LayerTopLevel	LayerBottomLevel	LayerDepth
2	1	0	0	0	0	-10	1	0	-10	-10
3	2	100	100	3	0	-10	1	3	-7	-10
4	3	0	100	5	0	-10	1	5	-5	-10
5	4	100	0	2	0	-10	1	2	-8	-10
6	5	25	25	6	0	-5	1	6	1	-5
7	6	25	75	2	0	-10	1	2	-8	-10
8	7	75	25	12	0	-5	1	12	7	-5
9	8	75	75	15	0	-10	1	15	5	-10
10	9	50	50	10	0	-10	1	10	0	-10
11	1	0	0	0	-10	-20	2	-10	-20	-10
12	2	100	100	3	-10	-15	2	-7	-12	-5
13	3	0	100	5	-10	-15	2	-5	-10	-5
14	4	100	0	2	-10	-20	2	-8	-18	-10
15	5	25	25	6	-5	-15	2	1	-9	-10
16	6	25	75	2	-10	-15	2	-8	-13	-5
17	7	75	25	12	-5	-10	2	7	2	-5
18	8	75	75	15	-10	-20	2	5	-5	-10
19	9	50	50	10	-10	-20	2	0	-10	-10
20	1	0	0	0	-20	-30	3	-20	-30	-10
21	2	100	100	3	-15	-30	3	-12	-27	-15
22	3	0	100	5	-15	-30	3	-10	-25	-15
23	4	100	0	2	-20	-30	3	-18	-28	-10
24	5	25	25	6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Figure 45: Part of the borehole datasheet for organizing data for subsurface 3D modelling

4.1.2 Borehole object

Before talking about how modelling the borehole elements was done and how the parameters were attached to it, it is significant to mention how the borehole element was created in the BIM platform Revit. It is also important to note that the NBS BIM Object Standard was taken into consideration when creating the borehole object (NBS, 2019) (see fig. 46).

3.1 General

3.1.1 **Modelling scale**

The BIM object shall have geometry produced at the scale 1:1.

3.1.2 **Insertion point**

The BIM object shall include an insertion point that is suitable for its intended use.

3.1.3 **Parametric function**

The BIM object may, where supported by the BIM platform and where appropriate:

a) Have parametric geometry that is locked and aligned to appropriate reference elements such as planes, lines, levels and points.

b) Include dimensions and labels that are constrained to reference planes.

3.1.4 **Modelling units**

The BIM object shall use metric geometry with units of millimetres, unless the local construction industry has (without dispute) retained an alternative unit of measurement.

Figure 46: Part of standards for BIM objects from NBS BIM Object Standard

The definition of a BIM object was explained in a previous chapter, however, it was not mentioned in the context of the Revit platform, hence it is important to describe how BIM elements work there.

Revit uses categories, families, types, and instances to organize BIM objects. Everything in the Revit model is considered as an object, including 3D elements, 2D elements, views, and sheets. However, any object type belongs to a well-organized hierarchy that sorts out data in models.

Revit element hierarchy has four main levels: Category, Family, Type, and Instance (see fig. 47). A Category controls the organization, visibility, graphical representations, and scheduling options of families in a project. A Family is a grouping of 2D and/or 3D information that serves to represent a discrete building or documentation element in the Project. It defines parametric, graphical, and documentation requirements.

A Type is a specific representation in a Family defined by distinct parametric, graphical, and documentation characteristics which makes it unique from other Types in the Family. An Instance is an individual representation of a Type in the Project defined by unique parametric, graphical, and documentation characteristics which makes it unique from other Instances in the Project.

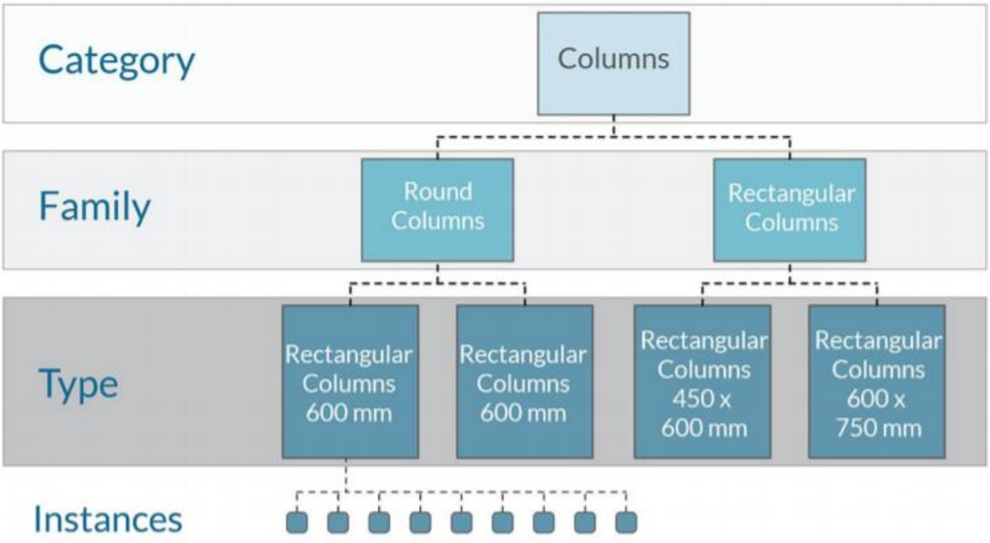


Figure 47: Revit Object Hierarchy (DynamoPrimer 2019)

There are three kinds of Revit families: System, Loadable, and Inplace. System families contain family types that you use to create basic building elements such as walls, floors, ceilings, and stairs in your building models. Loadable families, unlike system families, are created in external RFA files and imported (loaded) in your projects. In-place families are custom elements that you create in the context of a project.

Revit Hierarchy uses parametric modelling to define family types and instances of objects. Parametric modelling is a way of modelling an object with certain flexibility. Some aspects of the object are defined by parameters, these parameters are open to being modified and to be related by formulas. As an example of a parameter assigned to an instance, in Figure 48 a BIM object that represents a door. This door is the same object type with multiple type instances, each one with different dimensions defining the height and the width for the same model. This flexibility in parametric modelling is very relatable in this work to create a borehole object that is meant to represent different boreholes of different lengths.

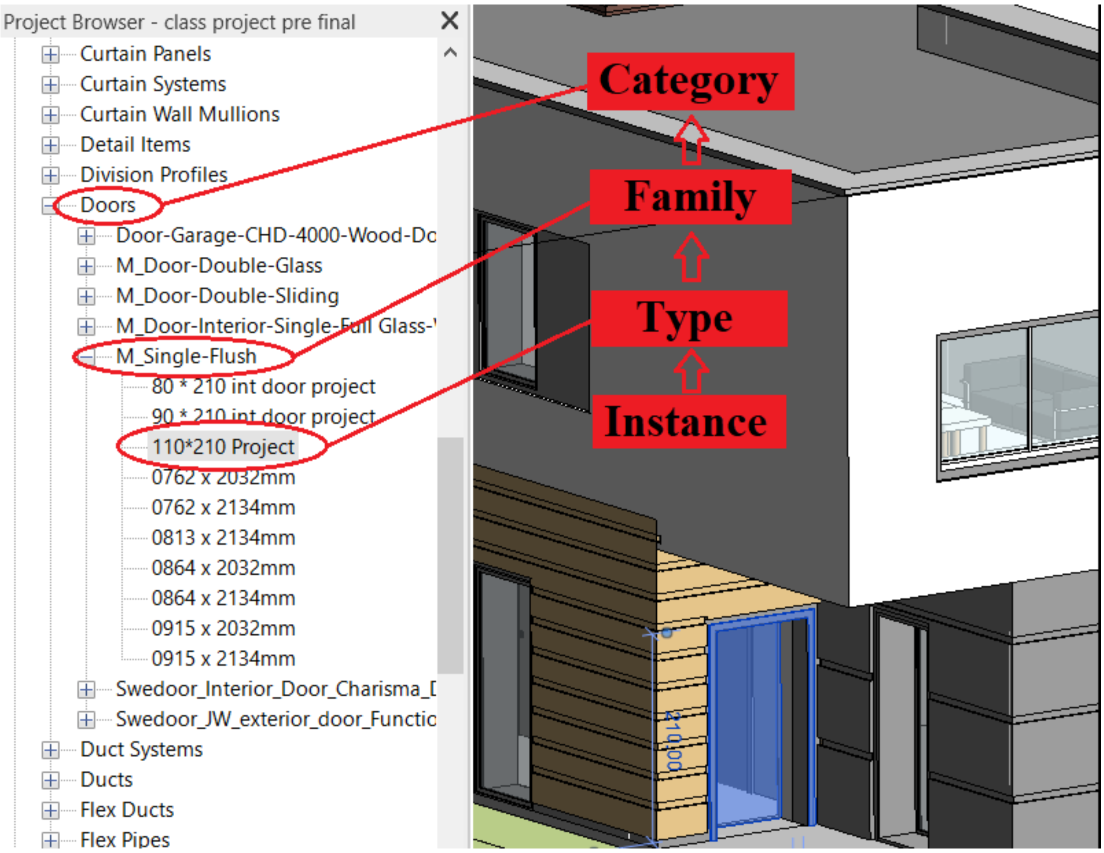


Figure 48: Hierarchy of a door as a BIM object in Revit

It was intended to create a family-type to represent the borehole, however, since in the Revit platform no category or family represents boreholes, an alternative type had to be found. Two choices were considered for the representation of the borehole. The first is to put it under the category of “Generic models” which is usually used for objects that are not found in the pre-defined categories in Revit. The second choice, which is what was opted for, was to choose the category “Column” since the borehole shape resembles a circular column and it is almost always in a vertical position, and especially because the column can be defined as a non-load bearing object in the platform.

Hence an object of the category Column was created and given a Family name “Borehole”. The object had to be flexible in the height parameter since it will represent the top and bottom parts of different layers in boreholes and they would have different lengths. Hence, for that purpose, the top and bottom points of the borehole object were defined as adaptive points and the object was to be an adaptive component of two points (see fig. 49).

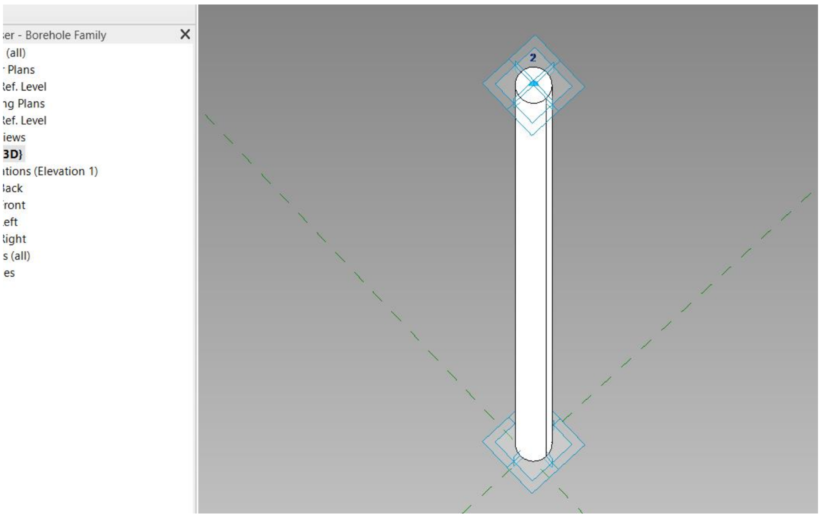


Figure 49: Borehole family created in Revit with adaptive points

Adaptive components are mostly used when there is a need to adapt a family to different positions in space following parametric rules (see fig. 50). A special feature is that, while in regular families the geometry is related to one unique insertion point; in adaptive components, it can be related to more than one. Consequently, the adaptive component can change shape depending on the specific position of those points. In the case of this work, the shape will only be modelled based on the position of the top and bottom points of layers in a borehole.

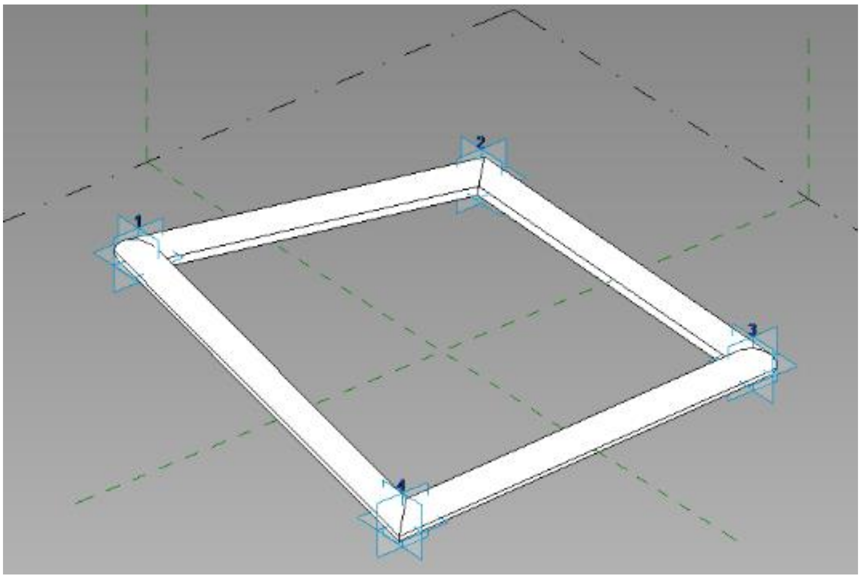


Figure 50: An object made with adaptive components (Molinos, 2016)

The next step after creating the borehole object was to create the parameters where all the geotechnical data from the PDT will be inserted. It is important to define first the types of parameters that can be used on objects in Revit and what are their characteristics, before indicating what type of parameters was chosen for the borehole object.

Parameters can be created for a project or any element or component category in the project. Parameters created are displayed in the Revit platform in the properties palette or Type Properties dialog under the group you define and with the values assigned to each parameter. Revit has a set of pre-defined property groups for parameters (groups construction, Materials and Finishes, and Dimensions are shown in fig. 51), and it is not possible to create new groups as per the project needs. This is a common issue when proposing a new set of parameters and the user would want to define them under a new group that does not exist in the platform.

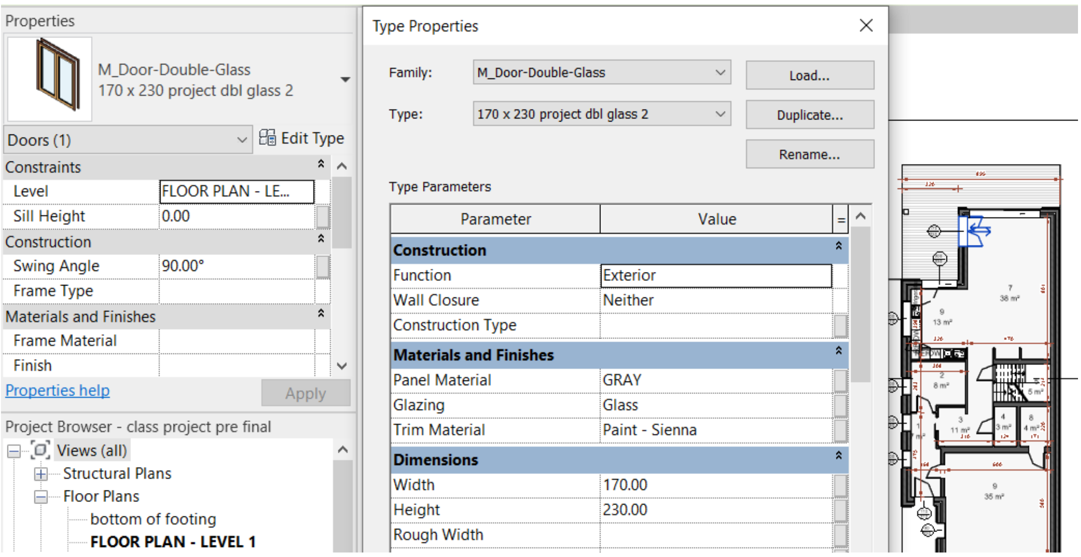


Figure 51: Predefined property groups of parameters in Revit

The subject of group definition was an issue for this work as it was intended to put each set of parameters under a specific group like for example placing all the Strength Lab Test Results under a group of that name, but it was not possible and a pre-defined group in the program had to be chosen. However, for exporting the object parameters in IFC format it was possible to move around this issue using scheduling, more about this subject in part 4.3 Interoperability.

There are four types of parameters in Revit. The first type is the project parameters. These are specific to the unique project file and are added to elements by assigning them to different categories of elements, sheets, or views. Data stored in project parameters are not share-able with other projects. They are used for scheduling, sorting, and filtering in a project. The second type is the family parameters. These control non-stable values of the family, like dimensions and, are unique to the family they belong to. The third type is global parameters, and these are specific to single project files, but not assigned to categories. They can be simple values, derived from equations, or taken from the model using other global parameters.

The fourth type is the shared parameters. These are parameter definitions that can be used in different families or even projects. When you add a shared parameter definition to a family or project, you can use these shared parameters as family or project parameters. The shared parameters are stored in a separate file than the project and hence protected from change. Shared parameters can be tagged and scheduled. This type of parameters was used to create the borehole object parameters (see fig. 52), because to be able to schedule parameters is important for the object as it will help us in exporting the parameters later on in IFC format as discussed in part 4.3.

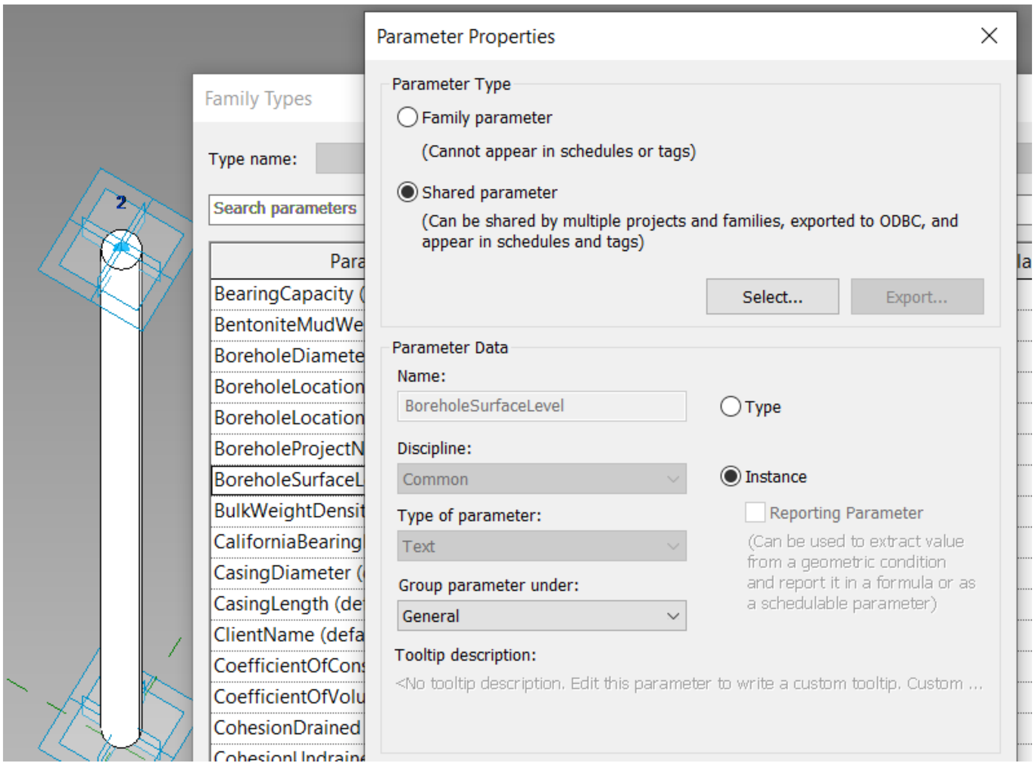


Figure 52: Shared parameter type in Parameter Properties in Revit

Every parameter was introduced as a shared parameter to the project and the name, type, and group are assigned to it. Then it is required to choose if the parameter would be a type or an instance parameter. The type parameter enables you to modify the parameter value, which applies to all elements of the family type. The instance parameter enables you to modify the parameter value for each instance separately. The instance parameter option was chosen as it fits more with the object created since each element in the same family can have different parameter values.

Now that the borehole datasheet and borehole object are created, the next step of the work was creating the algorithms needed in the visual scripting software Dynamo to model the boreholes and extract the data from the excel sheet and insert it into each created element in the BIM platform.

4.2 Algorithms in scripting program to model boreholes and subsurface layers

4.2.1 Algorithms of modelling boreholes with geotechnical data

The 3D modelling of borehole elements in the BIM platform is one of the main outcomes of this work, especially that these elements will hold all the important data that was derived from the geotechnical investigation report. The first task to accomplish this is to transfer the data found in the proposed excel sheet to the scripting program, Dynamo. The second step is to use the location data of the boreholes from the excel sheet to model the physical entity of the boreholes in the BIM platform. The third and final step is to make a relation between the parameters created in the borehole object and the parameters extracted from the excel sheet to populate the parameters with their respective data in all the borehole elements created in the BIM platform, hence having borehole elements with geotechnical data as parameters as a result.

In the first step, to transfer data into Dynamo from an external source, there are pre-existing nodes in the library of the program that has been created to fulfill that purpose (see fig. 53). These nodes are made to extract data specifically from Excel. After using these nodes, however, The data needs some refining and organizing using other available nodes in the program so that the data is segregated as per the needs of the user and organized in a matter that makes it easy to handle this data.

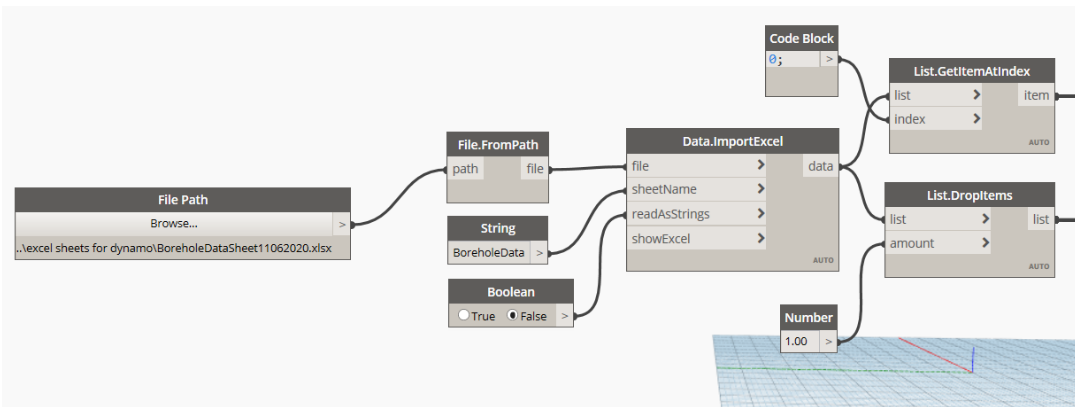


Figure 53: Set of nodes in Dynamo to extract data from the Excel sheet

For the second step, which is to use the location data of the borehole to model the physical form of the boreholes using the created family, the data that represent the northing, easting, depths of top and bottom of each layer in the borehole and the level of the borehole was extracted and segregated separately using the tools and nodes available in the software (see fig. 54). After that, a node to create two sets of points was used, the first representing the point coordinates of the top of each layer in a borehole, and the second is the same but for the bottom of each layer. Consequently, having the coordinates necessary to model each layer in a borehole independently using the top and bottom points. Keeping in mind that a borehole object that can be controlled and modelled using two adaptive points, the top and bottom of the borehole, was already created.

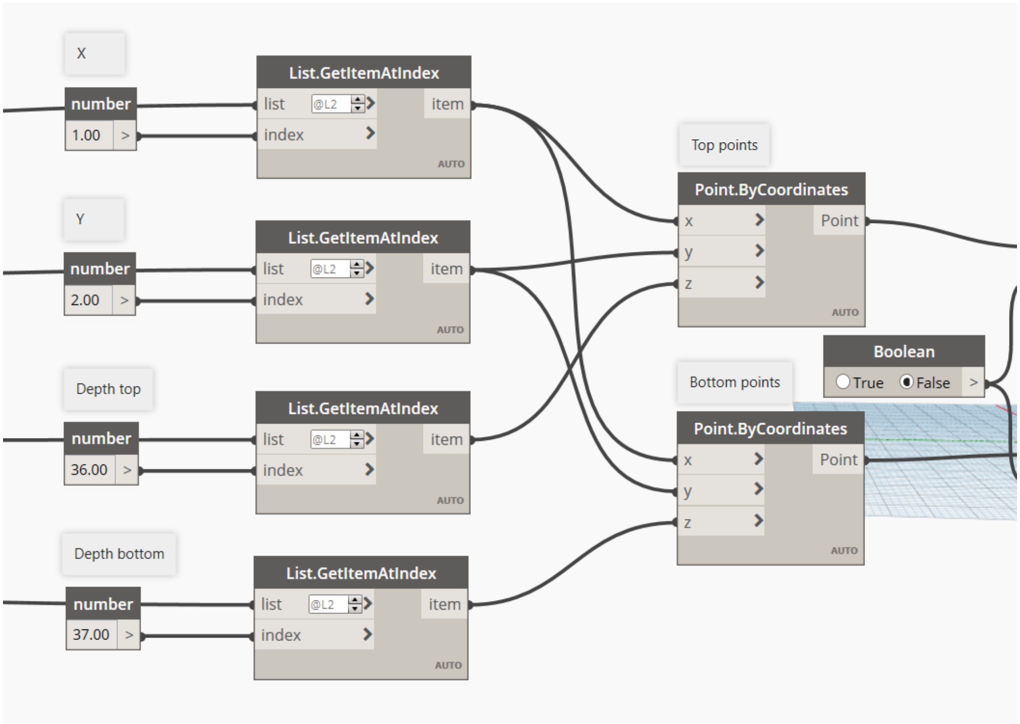


Figure 54: Set of nodes in Dynamo to combine borehole coordinates data to form points

Then the borehole family created was imported into Revit, outside of Dynamo, this is important to call upon the family from Revit and use it through Dynamo. Then in Dynamo, a specific node was used to model the borehole family as per the adaptive component's coordinates which was arranged in the nodes before (see fig. 55). After running the program the borehole elements created in the BIM platform can be seen, however, there is no data in the parameters section of each borehole, which takes us to the third step.

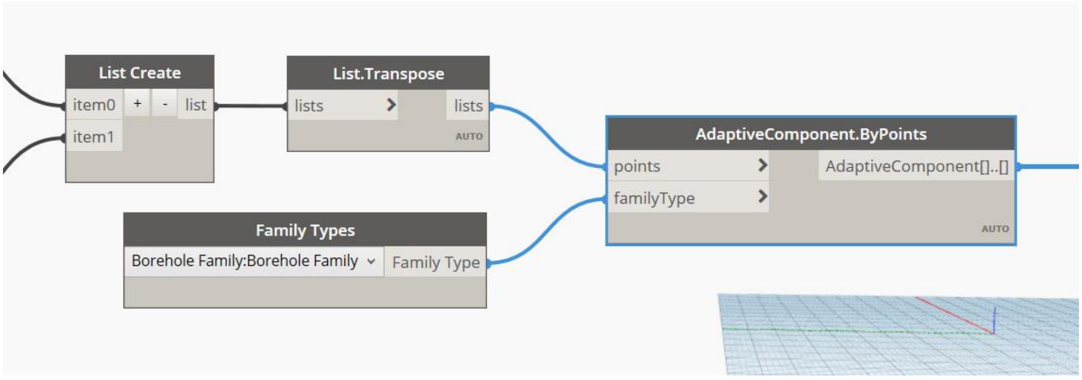


Figure 55: Nodes in Dynamo to model borehole family using adaptive components

The third step was to make a relation between the parameters of the created borehole elements and the parameters extracted from the excel sheet. The best method to populate the parameters is to make a relation between the name of a parameter in the borehole family and the name of the parameter in the Excel sheet since they are identical. Therefore the names and values were extracted from the Excel sheet and then it was used a specific node to populate the parameters of the modelled boreholes based on the parameter name (see fig. 56).

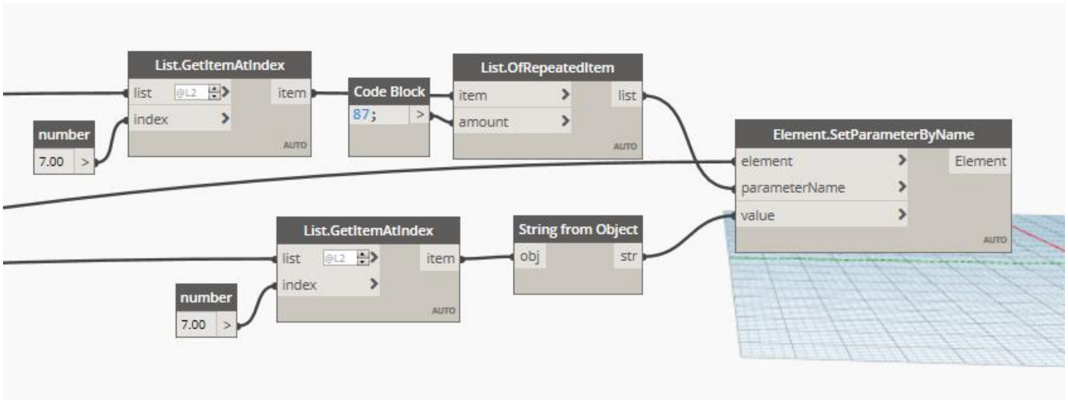


Figure 56: Set of nodes in Dynamo to populate parameters in borehole family

This process was repeated 104 times in Dynamo, as much as the number of the parameters in the borehole element. As a final result, the borehole element with populated parameters representing the geotechnical data collected from the geotechnical investigation can be seen in figure 57, and the final Dynamo code in figure 58.

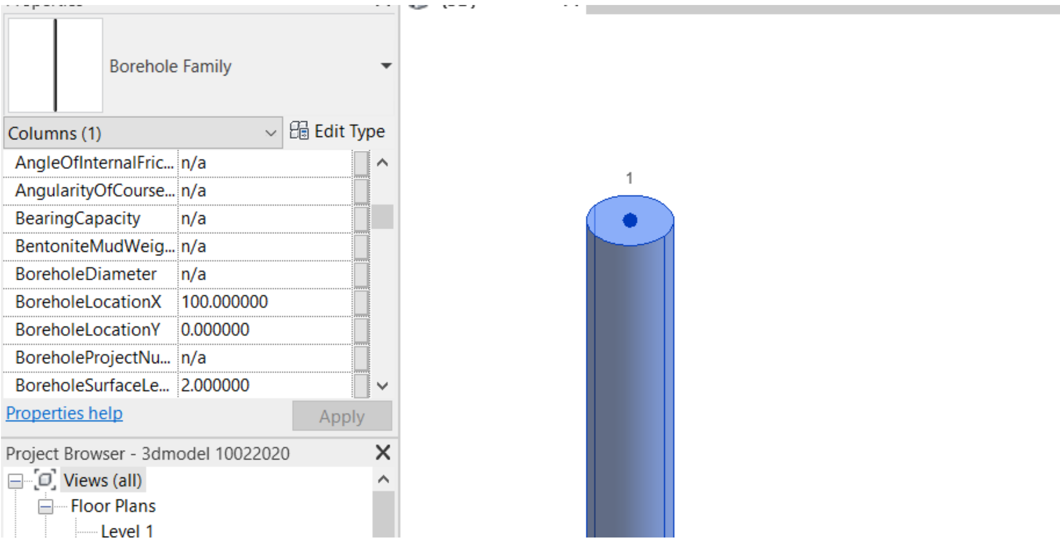


Figure 57: Borehole family with parameters in Revit

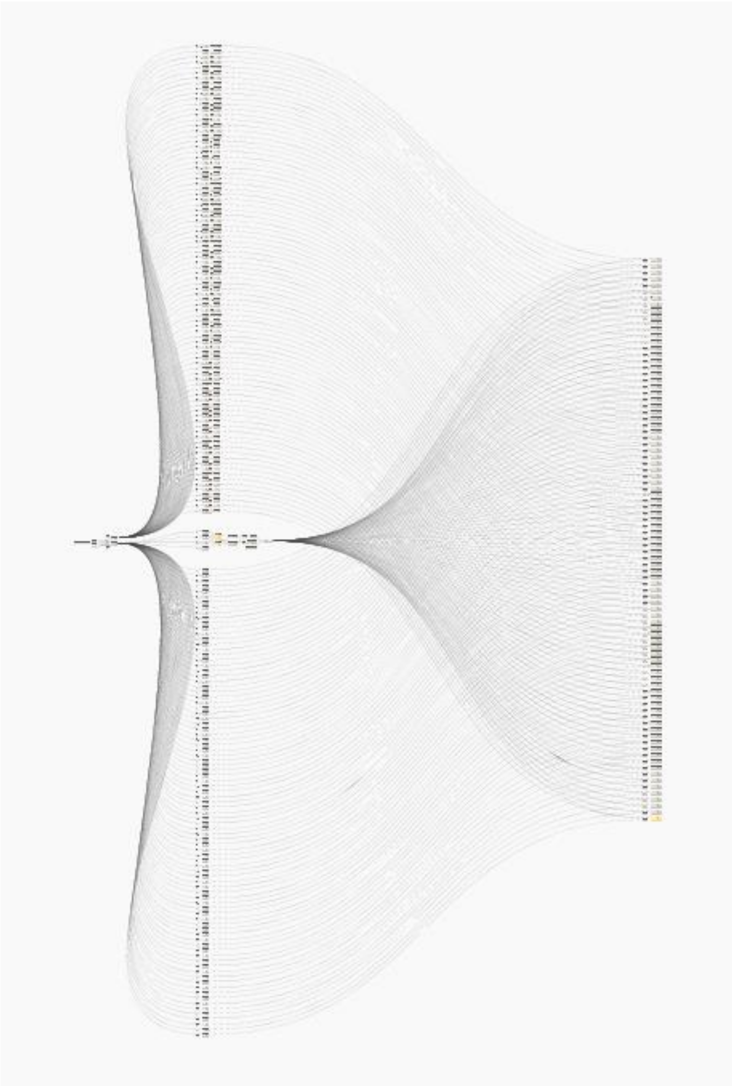


Figure 58: Dynamo Script for modelling boreholes with parameters

4.2.2 Algorithms of modelling subsurface layers

The 3D representation of the underground earth layers is an important aspect for different stakeholders, but especially for designers in the initial stages of any project, as it helps in visualizing the layers and detect any problems that can be faced in the future due to the different formations of subsurface layers. Many software in the market that is directed toward geotechnical engineering works is adapting to include 3D visualization of underground layers, as it has shown great benefits as discussed earlier.

For the 3D modelling of the underground layers, it was created a scripting code that exports the information of the boreholes from the borehole datasheet and creates a solid form to represent each layer accordingly. However, this process required many modifications on the excel sheet as work progressed and it required many trial and error processes in Dynamo so that the final result reached was somehow satisfactory for this work.

It is important to define how Dynamo processes work to create 3D objects. Dynamo creates geometry in a systematic manner where drawing a 3D object starts from a simple dot, then from several dots, it creates lines and from several lines, a plane or surface, and from that surface or multiple surfaces, it is possible to create a 3D object (see fig. 59). It is simple in concept but the execution of complex geometry requires complex algorithms for the arrangement of data to follow that systematic way of processing.

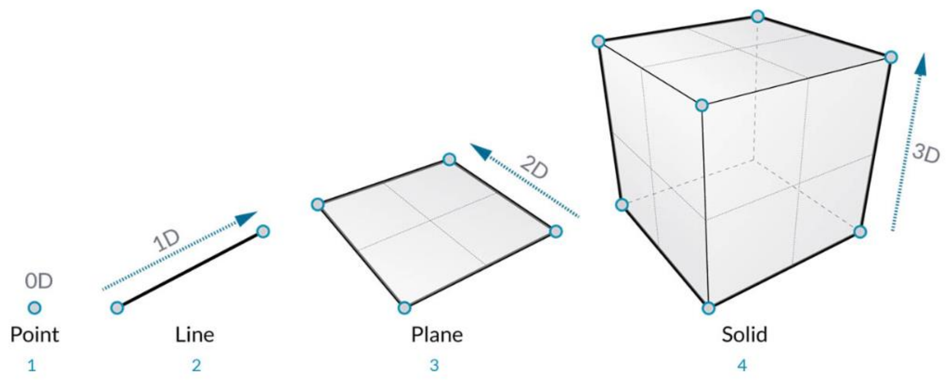


Figure 59: Dynamo's methodology in 3D solid creation (DynamoPrimer, 2019)

In this work, the main data that can be relied on for modelling the subsurface layers are the coordinates of the boreholes for the X and Y axis, and the level where each layer starts and finishes for the Z-axis. Accordingly, it was created a new page in the Excel sheet that takes the data necessary from the main borehole datasheet and calculates the coordinates necessary that represent each layer start and finish in all the boreholes (see fig. 45).

Having the coordinates of the points of the layers in the boreholes, the next step was to create a connection between all the points of the same layer to create a surface that represents the top and bottom of each layer. Since working with data similar to topographic data, it was useful to use the specific node in dynamo that is made for modelling topographic surfaces. The points representing the start of a layer was used to draw the surface representing the top of the layer, and the same for the bottom (see fig. 60).

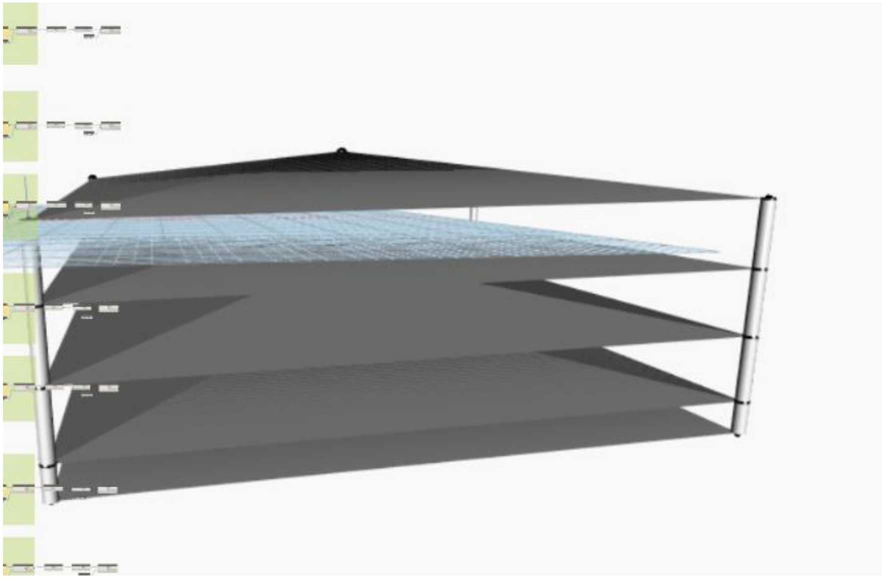


Figure 60: Snapshot from Dynamo showing top and bottom surfaces of subsurface layers

The created surfaces were then divided into triangulated parts using the mesh node in Dynamo, this allowed us to have the top and bottom total surface be divided in triangulated small surfaces where each two triangular surfaces top and bottom would be enough to create a solid mass between them (see fig 61).

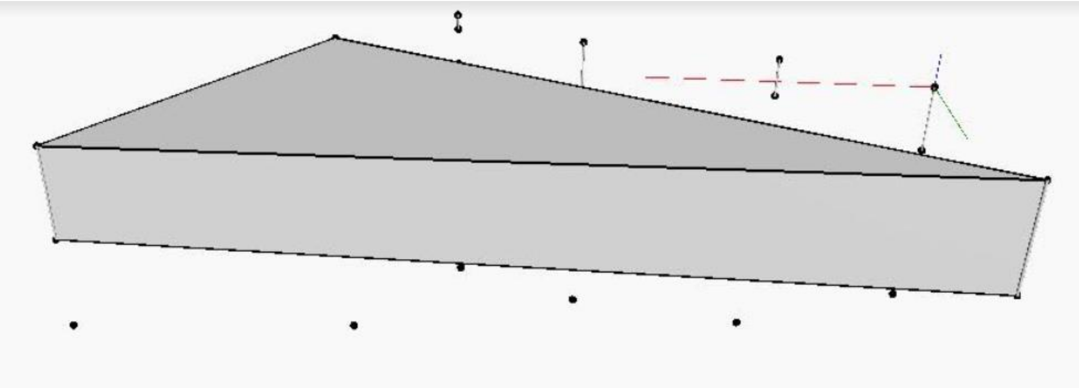


Figure 61: Creating solids of triangulated parts of the subsurface layers in Dynamo

After the creation of all the solid masses, a specific node was used to unify all the solids into one, representing the subsurface layer being modelled. The same logarithm was repeated as per the number of layers existing in the model (see fig. 62). The resulting solid mass was then exported into Revit. Additional nodes were used also to add a color to each layer to make the model visually easy to understand and analyze (see fig. 63).

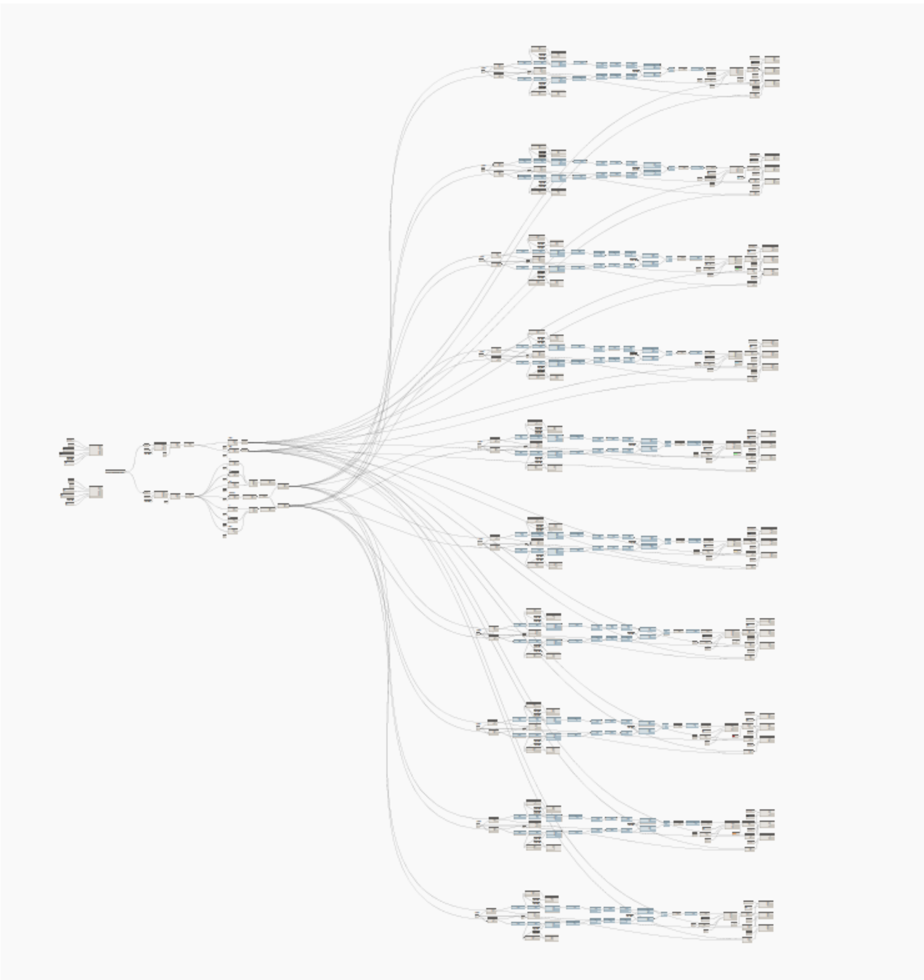


Figure 62: Script for modelling subsurface layers in 3D in Dynamo

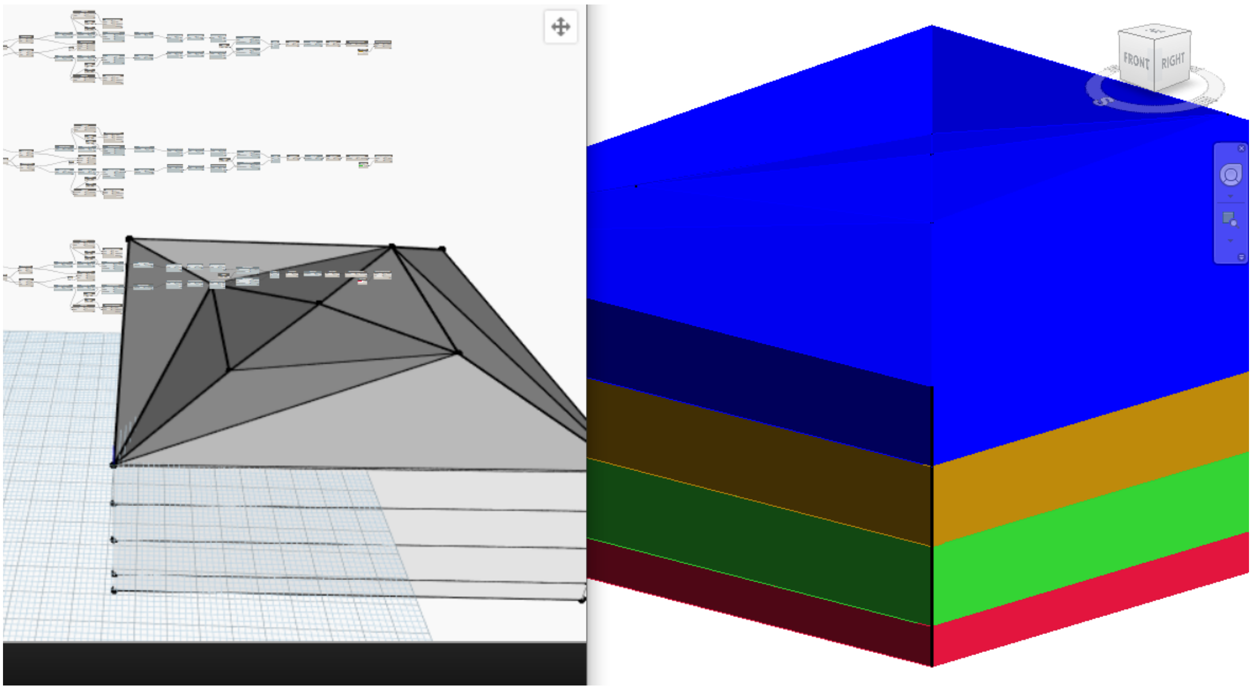


Figure 63: Subsurface layers as 3D objects in Revit and Dynamo

The result of the program was solid masses representing different layers of the subsurface, these masses were exported in Revit as "Site" family type, as it seemed a convenient family to represent subsurface layers. To identify the characteristics of these elements that represent different subsurface layers easier for the user, two parameters which identify the soil or rock type of each layer were added using the scripting code by creating two new Project parameters specifically for the subsurface layers elements and their corresponding values were extracted from the excel data sheet (see fig. 64).

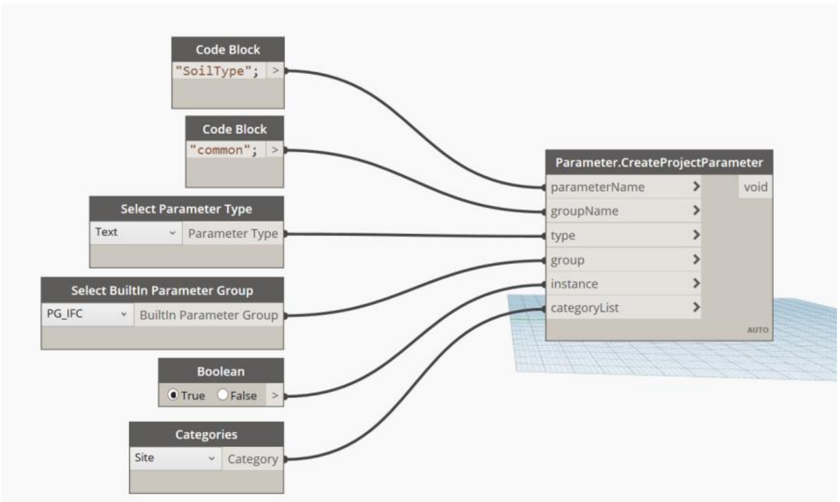


Figure 64: Nodes in Dynamo to create Project parameter "SoilType" for subsurface 3D elements

The subsurface layers modelled in Revit was not meant to have all the parameters that are present in the borehole element, since it is connected to different boreholes that can have different parameters and test results, yet since they all share the same soil or rock type, these two parameters representing the soil or rock type was chosen to be added to the subsurface layers (see fig. 65).

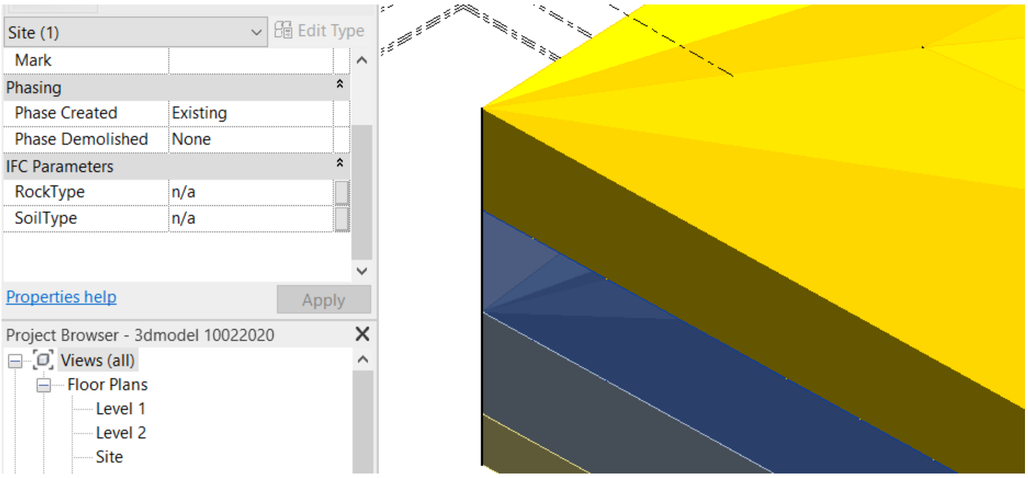


Figure 65: SoilType and RockType parameters for 3D subsurface elements in Revit

After finalizing the algorithms of modelling the boreholes and subsurface levels, it was created nine different boreholes with four different layers as a simple example to test the written script. The result of the example was successful and it resulted in a model in the BIM platform with boreholes and subsurface layers in 3D with all the needed parameters attached to its elements (see fig. 66). The software however had to be tested for complex ground formations to help us discover where the written script can be developed and how it should be improved to tackle the problems that arose.

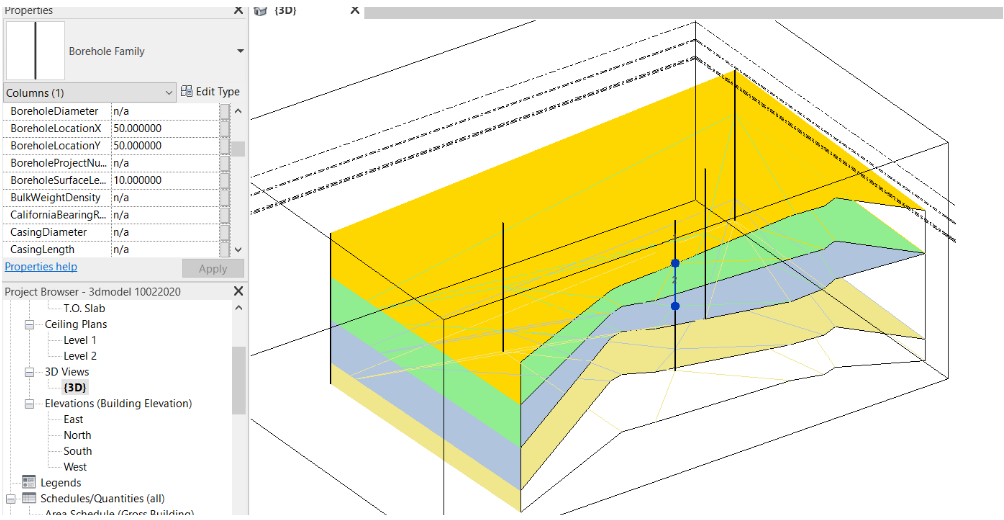


Figure 66: Model of boreholes and 3D subsurface layers in Revit done from the data of the test boreholes excel sheet

To test the model in a more complex context one layer was removed from some boreholes and kept in others, to see how the program would model this data and what the outcome would be. The third layer from the excel sheet was removed from three different boreholes then the program was run on Dynamo to see the results (see fig. 67).

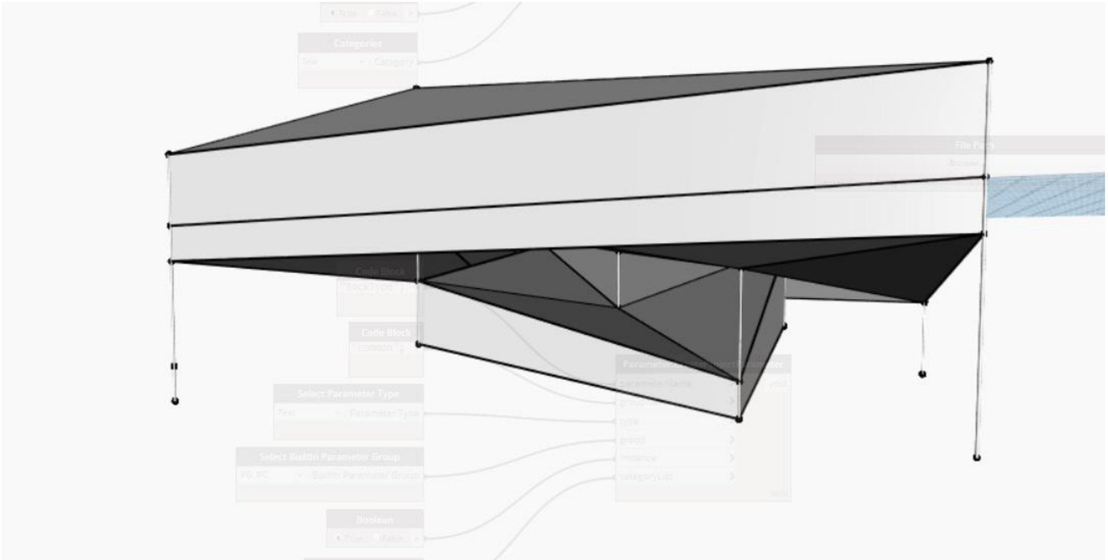


Figure 67: Results in Dynamo with removed layers from multiple boreholes

The result of this change caused the disappearance of the third layer completely because the logarithm created relies on the presence of an upper layer and a lower layer for all boreholes to be able to create the surfaces and then the solid masses.

Other software that also has the option of modelling subsurface layers from borehole data was analyzed to observe how this problem was dealt with, and it was found that the same problem existed when the data of the boreholes presented a layer that is not existing in some boreholes and exists in others (see fig. 68). The solution in other software was to edit the model manually to get the desired result.

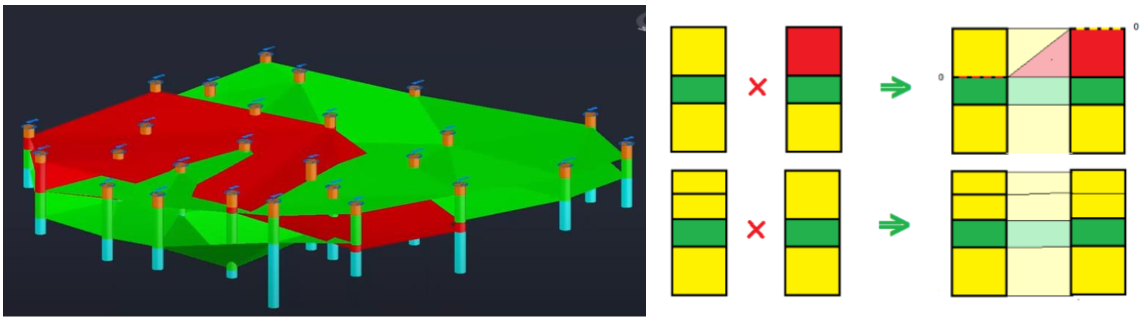


Figure 68: Model in Civil 3D with layers intersecting because of irregular borehole data (Keynetix, 2015) (left) and an example of how boreholes should be created to be compatible with same layer numbers in Geo5 software (Fine, 2020) (right)

Hence it was explored a way to find a solution for this problem, without the need for manually editing the model. As per the logarithm written and how its sequence is made, it was understood that the same layers needed to exist in all the boreholes. Hence it was important to for the 3D model to work, to choose a borehole that includes all the layers of the model and use it as a reference for the other boreholes, this way all boreholes will have the same sequence of layers.

But a way had to be found to put the data in a way that does not show these layers, where they don't exist. Hence the layers that did not exist in some boreholes were given a zero thickness to see how the program would read the data. After the data was edited the program was run again and the results were positive and the program shows the boreholes with missing layers having only 3 subsurface layers in the model (see fig. 69). It is possible to see in figure 68 that one side has 4 layers and the other has only 3.

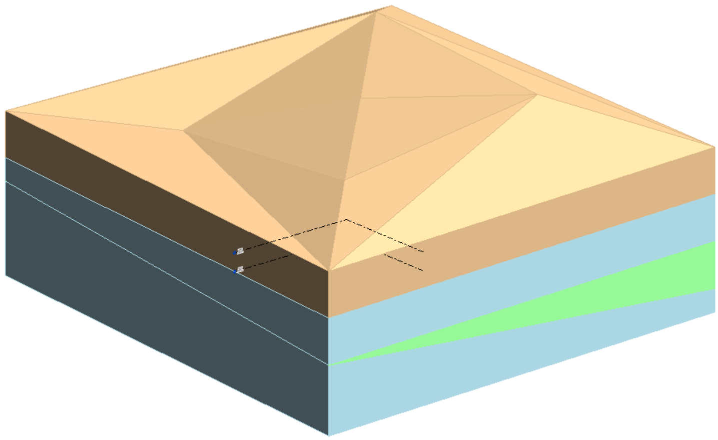


Figure 69: Model in Revit with boreholes having a different number of layers

This means that for the program to work, there should be done some analysis for the boring logs to understand what are the existing layers in the ground and fill the borehole excel sheet accordingly. It does require more time from the user, but as noticed in other programs, to handle this issue there will always be a need for human interference to solve these issues that the program can not solve on its own.

4.3 Interoperability

The geotechnical information which was extracted from the geotechnical reports and saved in the created model should be preserved in an interoperable format to attain the goal of preserving this information for use by different stakeholders and any future use by any user regardless of the platform they intend to use.

For that purpose, the guidelines set by the NBS BIM Object standard for exporting data in the IFC format was followed. As mentioned earlier, the BIM platforms and tools currently do not give the right attention to the aspects of modelling elements related to infrastructure and underground elements, and because of that it was not possible to export the boreholes in an IFC type specifically created for boreholes or subsurface layers like IfcBorehole or IfcSubsurface, as it did not exist.

To export the created elements the type options available for the borehole element and subsurface layers were explored. The NBS standards state that if the type of element modelled does not exist in the IFC library, the object type "IfcBuildingElementProxy" can be used instead (see fig. 70), another choice was to identify the borehole family as an "IfcColumn", as the boreholes are created from a family object which is defined as a column and it resembles the geometrical shape of a column.

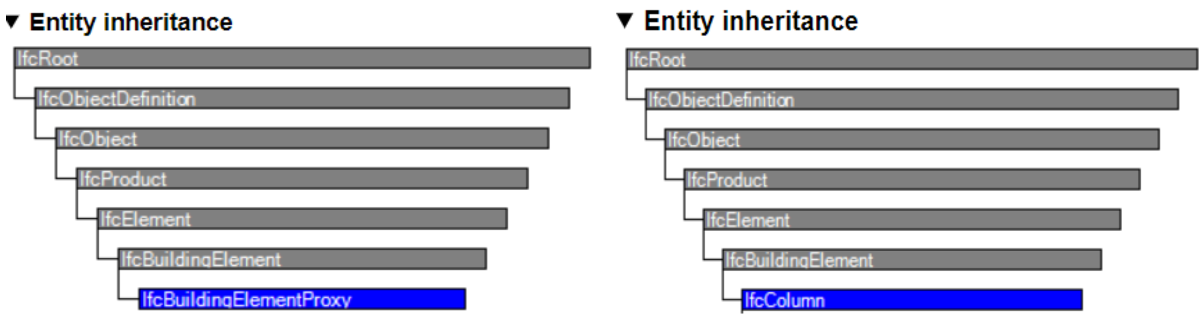


Figure 70: IFC inheritance for IfcBuildingElementProxy and IfcColumn (BuildingSMART, 2020)

As per this information, it was decided that the family that is currently defined as a column in the BIM platform will be exported as an "IfcBuildingElementProxy" type since as per the guidelines it is an element that does not exist in the IFC library. If in the future a specific IFC type for boreholes emerges, it can be substituted. The subsurface layers which were defined as Site family will be exported under the type "IfcSite" as it fits the element type created. The type of each element when exported can be defined in the export properties (see fig. 71).

The use of "IfcBuildingElementProxy" as the export type for all column types in the model however will represent a problem if the model exported contains other column elements, since normal columns should be exported as "IfcColumn" and not "IfcBuildingElementProxy". The user must be aware that an export with the defined export properties should only be done for pure geotechnical models that do not have any other elements defines as columns in the model.

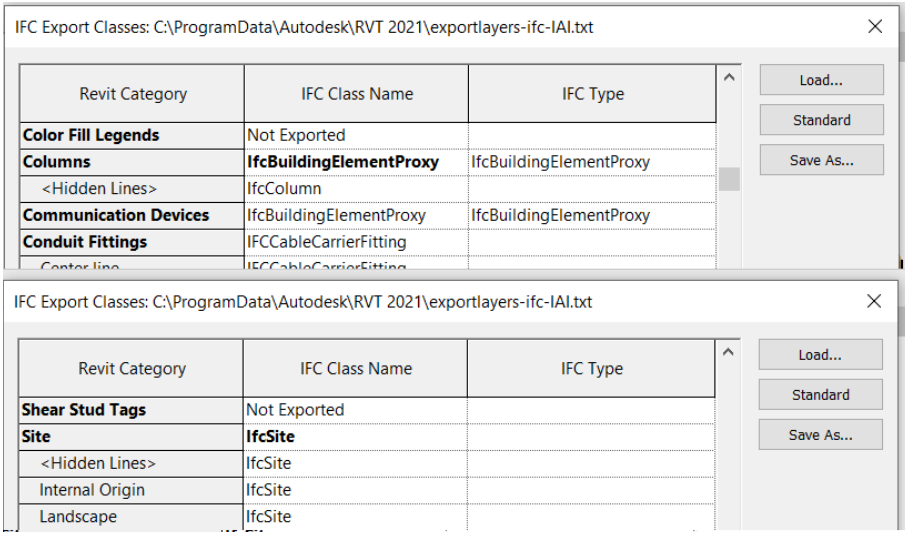


Figure 71: IFC export types of Boreholes and Subsurface layers

After defining the type each element will be exported in, the export IFC command in Revit was edited and the settings under which the export will be done was changed (see fig. 72). In general settings, it is possible to choose the IFC version that the model will be exported in. This is an important setting as the function of the model changes depending on the version chosen.

There were six principal releases of the IFC since the first version in 1996: IFC1.5.1, IFC2.0, IFC2x, IFC2x2, IFC2x3, and IFC4 in 2013. IFC5 is currently in the early planning phase, it is expected to include full support for various infrastructure domains and more parametric capabilities. The latest version, IFC 4, is recommended for all current developments, which is fully backward compatible with older versions. IFC 4 has two types of export, IFC 4 reference view and IFC 4 Design Transfer view (BuildingSmart, 2019).

The main purpose of the IFC4 Reference View is to define a standardized subset of the IFC4 schema, a Model View Definition MVD, that is particularly appropriate for all BIM workflows that are based on reference models where the exchange is mainly one-directional, and where requested modifications of the BIM data, are handled by a change request to the original author.

In the IFC4 Design Transfer View, which is the chosen version for this work, the recipient is supposed to be able to modify elements and spaces in the received model. Instead of just transferring geometric meshes the exported geometry must then be expressed as parameters that the downstream users can manipulate, this is particularly useful for model transfers between different software for performing different kinds of works on the same model. The IFC4 Design Transfer View is an extension of the Reference View model. In other words, the IFC4 Reference View is a true subset of the IFC4 Design Transfer View (BuildingSMART, 2019).

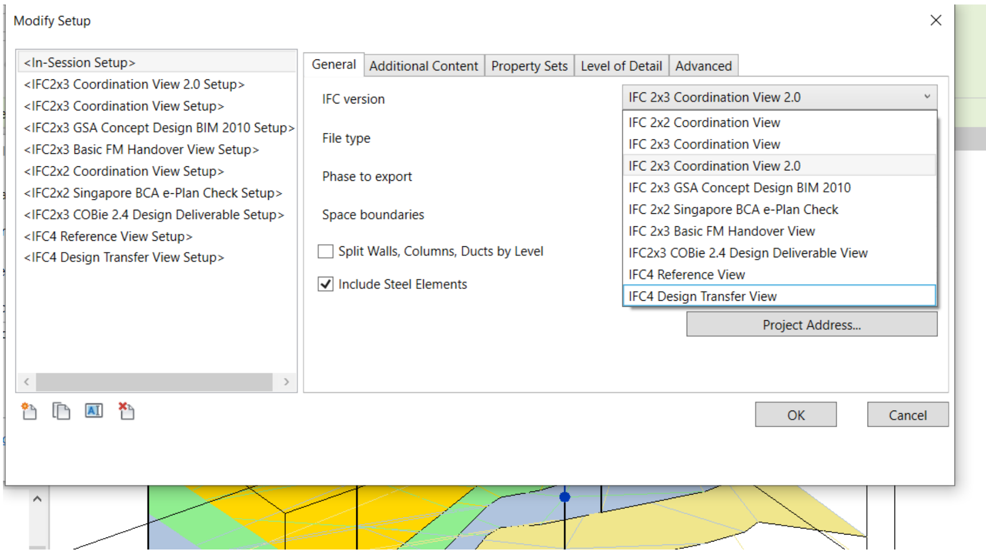


Figure 72: IFC general settings window showing IFC versions

Next, it was intended to export the parameters with the model, so the Property Sets part in settings was explored. There are various options for exporting parameters of BIM objects, however, the setting that fit the export needs at hand was in the setting “Export schedules as property sets” (see fig. 73). This specific option when applied allows the user to add any title to the schedules of the parameters. This means that a different schedule with a specific title related to each set of parameters to be exported can be created (see fig. 74).

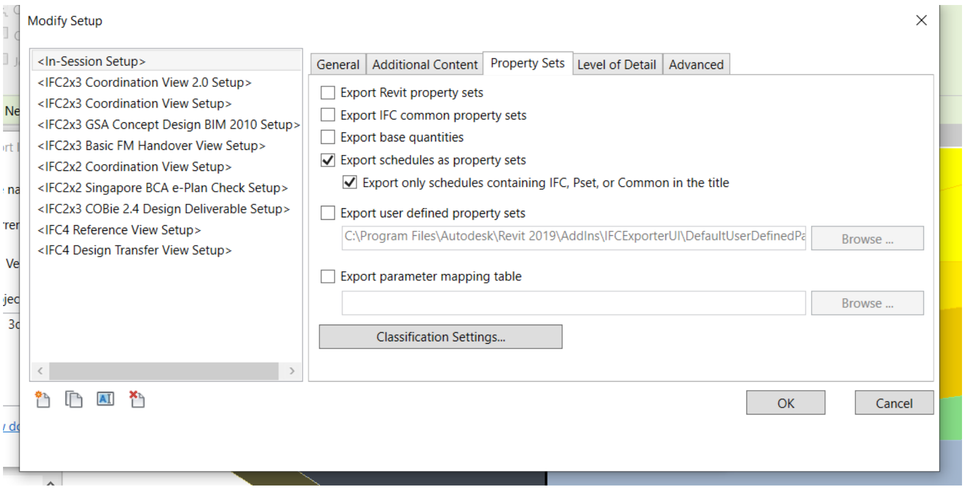
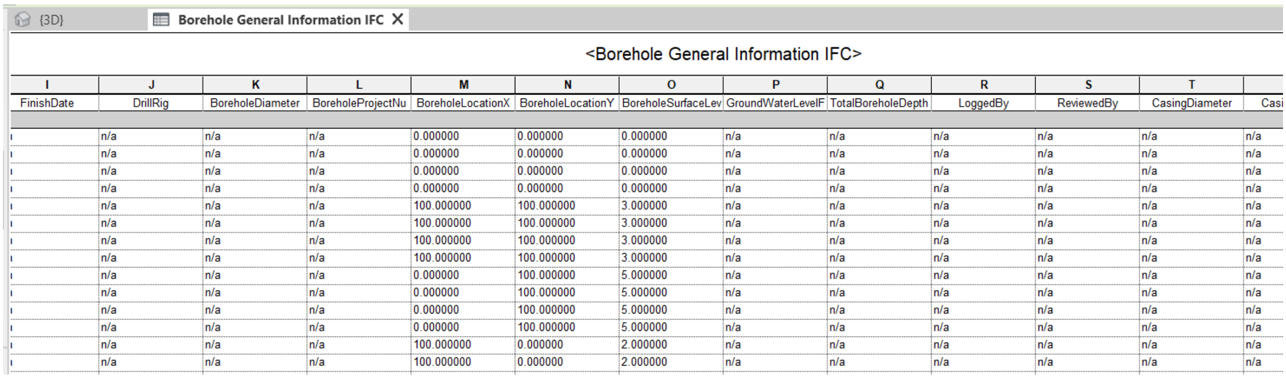


Figure 73: IFC Property Sets settings window showing property sets export options

This was one of the main reasons that the parameters type was chosen as “Shared parameters” because this type allows parameters to be put into schedules. The same method was adopted for the

“Project parameters” of the subsurface layers. It is important to note that these schedules can be saved in an external file and be uploaded into any Revit project, hence any user who has access to these schedule files will be able to smoothly export the model with parameters separated by group. The user can create their custom schedules as well to export the parameters that fit their specific needs.



<Borehole General Information IFC>

I	J	K	L	M	N	O	P	Q	R	S	T	
FinishDate	DrillRig	BoreholeDiameter	BoreholeProjectNu	BoreholeLocationX	BoreholeLocationY	BoreholeSurfaceLev	GroundWaterLevelF	TotalBoreholeDepth	LoggedBy	ReviewedBy	CasingDiameter	Casi
	n/a	n/a	n/a	0.000000	0.000000	0.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	0.000000	0.000000	0.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	0.000000	0.000000	0.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	0.000000	0.000000	0.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	100.000000	100.000000	3.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	100.000000	100.000000	3.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	100.000000	100.000000	3.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	100.000000	100.000000	3.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	0.000000	100.000000	5.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	0.000000	100.000000	5.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	0.000000	100.000000	5.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	0.000000	100.000000	5.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	100.000000	0.000000	2.000000	n/a	n/a	n/a	n/a	n/a	n/a
	n/a	n/a	n/a	100.000000	0.000000	2.000000	n/a	n/a	n/a	n/a	n/a	n/a

Figure 74: Schedule of parameters in Revit

After the creation of all the schedules for the different groups of the parameters of the borehole and the subsurface layers, the file was exported in IFC format. Then to test the file and see the result, a different platform than Revit was used called “BIM Vision”. The IFC file was imported into this program and it was possible to view the borehole objects and the 3D subsurface layers (see fig. 75).

A borehole element was selected, to confirm the presence of the parameters. As seen in figure 76 the element had all the parameters divided into groups as per the schedules made in Revit. The subsurface layers were selected as well to confirm the move of their parameters, and as seen in figure 77 the SoilType and RockType parameters are also present in the properties.

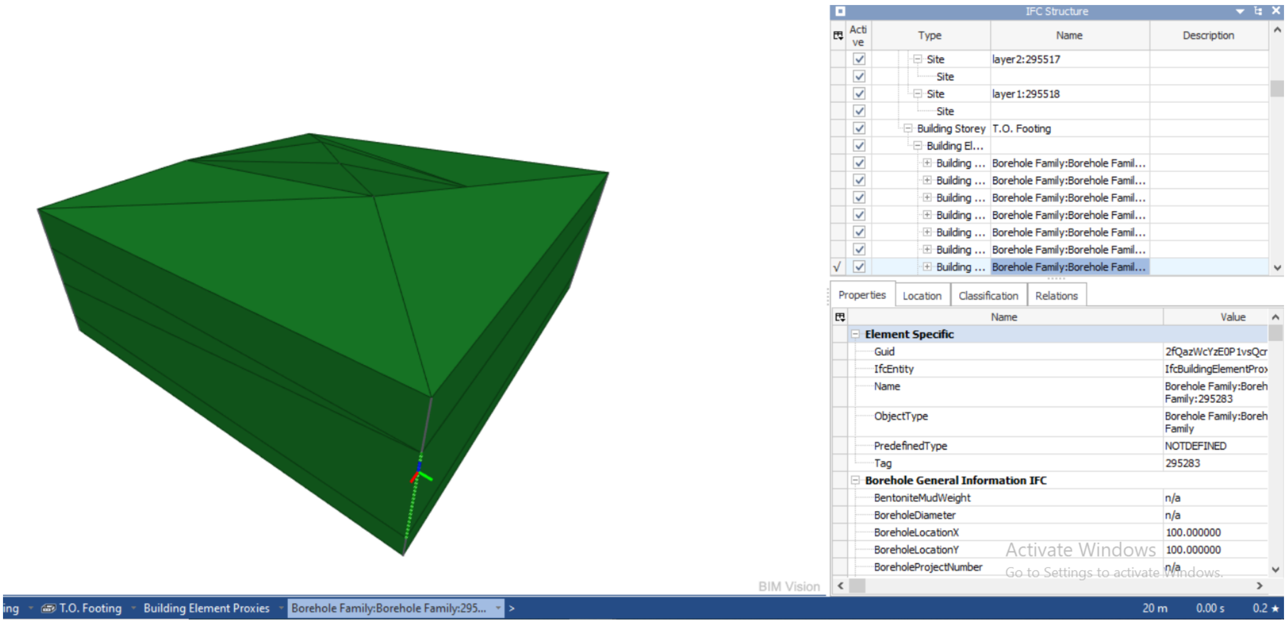


Figure 75: Boreholes and Subsurface layers in IFC format in BIM Vision

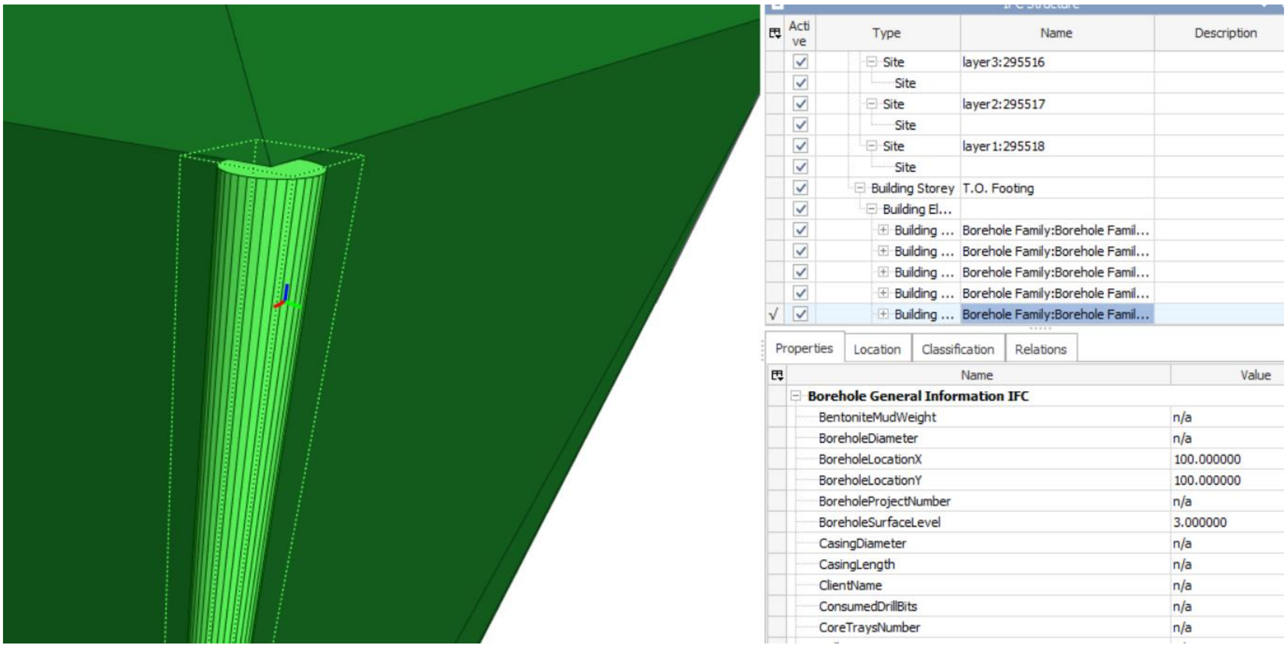


Figure 76: Borehole object in BIM Vision with parameters shown in properties

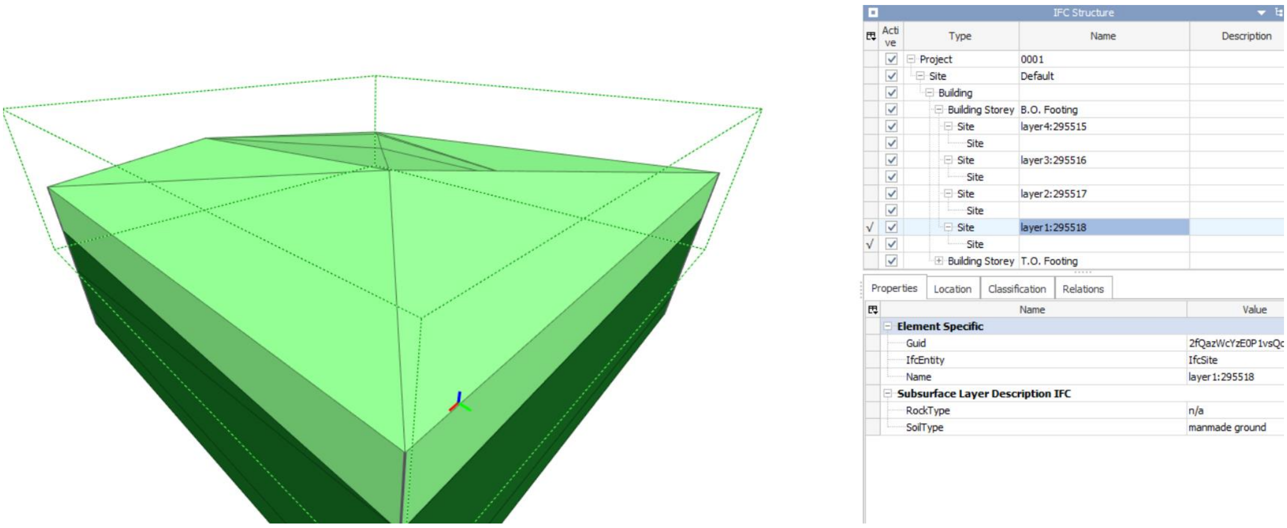


Figure 77: Subsurface layer object in BIM Vision with parameters shown in properties

It is important to address the issue of how can all of this data be extracted in the future from the IFC model. As it is one of the goals of the file being in IFC format is that the transfer of data works in two directions, importing and exporting. Extracting parameters of these elements back into Excel format is an added value. Data in Excel form is frequently needed in geotechnical analysis software for modelling or analyzing data, and having the data of the boreholes in an Excel sheet that can be edited or used in other software is a valuable asset.

Hence, the IFC file was opened again in the Revit platform and the same method of scheduling parameters was used to extract the data from the borehole elements and organize them as per the parameters groups they belong to (see fig.78). Then the schedules were exported as a text file, which can be copied and pasted directly in Excel to have as a result a table with the parameters exported from Revit (see fig. 79).

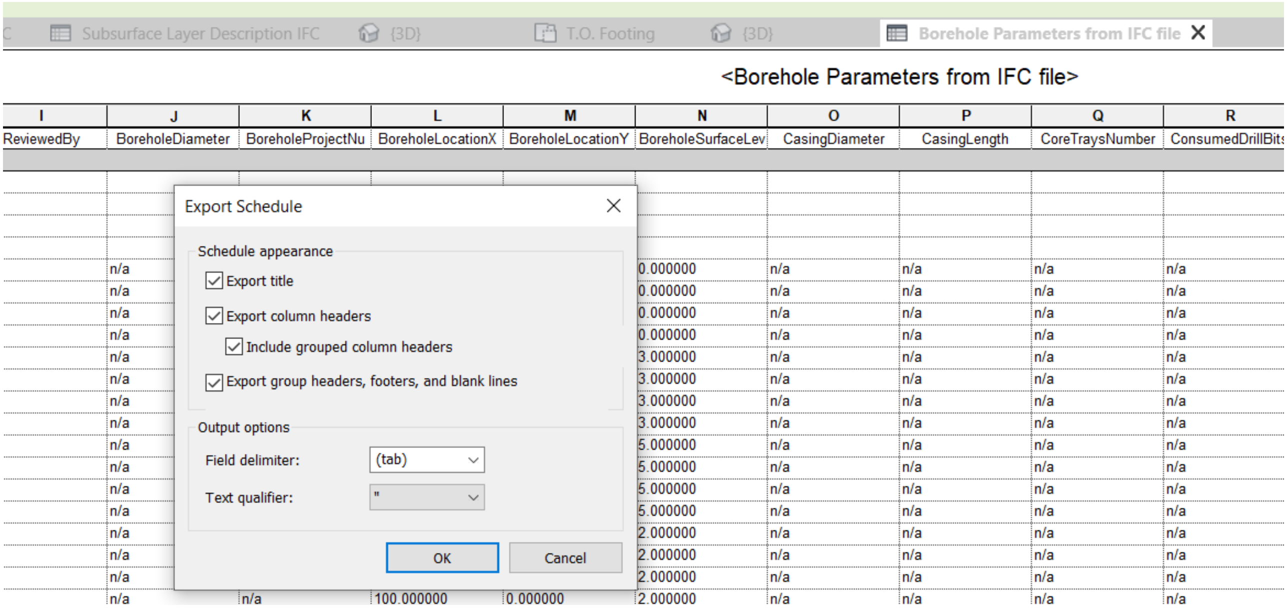


Figure 78: Scheduling of Parameters of the IFC file in Revit

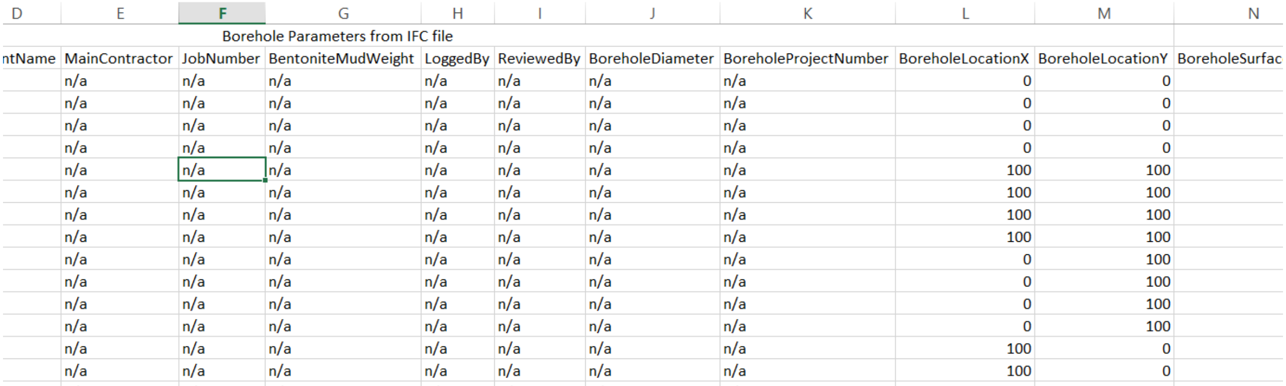


Figure 79: Excel sheet showing with the exported parameters from Revit

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5 CASE STUDY

5.1 The Project

The program that has been created for borehole and subsurface modelling was only tested on simple examples with little complexities and a limited number of boreholes. However, real earth layers are not as homogeneous and the type of soil can be different even in boreholes that are close to each other, and this causes bigger projects to have a bigger number of boreholes to show the different layers formations existing in their plots. The unpredictability in earth layers is the reason engineers want to visualize the data they have from geotechnical investigations so they can have the best idea of the composition of the subsurface layers in any project location.

A case study was performed with collection of data from a real project (kept anonymous in this dissertation) to study the results of executing the program created and understand its performance with real data. It is a project with four residential buildings built on one plot and they all share one basement that is on top of a raft foundation.

The geotechnical work done on the land was the preparation of the land for excavation by creating a parameter of secant piles that would be anchored with the progress of the excavation. It was done pressure grouting on the plot to decrease the permeability of the ground since the excavation would go beneath the water level of the area to create a raft foundation. Dewatering pumps were installed in wells and were operating around the clock until the raft was executed.

In 2012/13 the company responsible for the geotechnical investigation performed 8 boreholes on the plot to extract data for the geotechnical investigation report and to have a good idea of what are the earth layers in this plot (see fig. 80). The excavation depth for the project was around 9 meters, and the average depth of the boreholes was 20 meters. The borehole's locations were distributed around the site to have a good idea of the earth's layers.

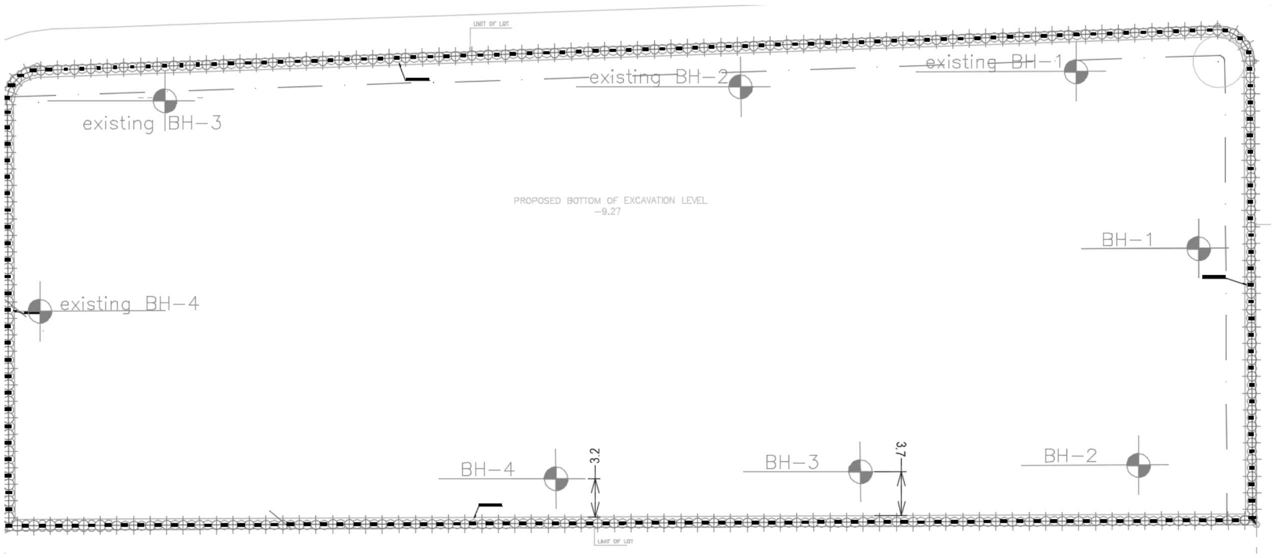


Figure 80: Boreholes location in the plot

The data necessary for this work was collected from the geotechnical investigation report of these boreholes as they were the most recent on the plot. Data was collected from borehole logs (see fig. 81), since these logs contain all the raw data collected from the boreholes in an organized sheet with information about the project, the borehole, coordinates, layers depths, tests made, layers description, etc. Moreover, data about laboratory and in-situ test results were also collected from the report since those results are not present in the borehole logs but in different schedules (see fig. 82).

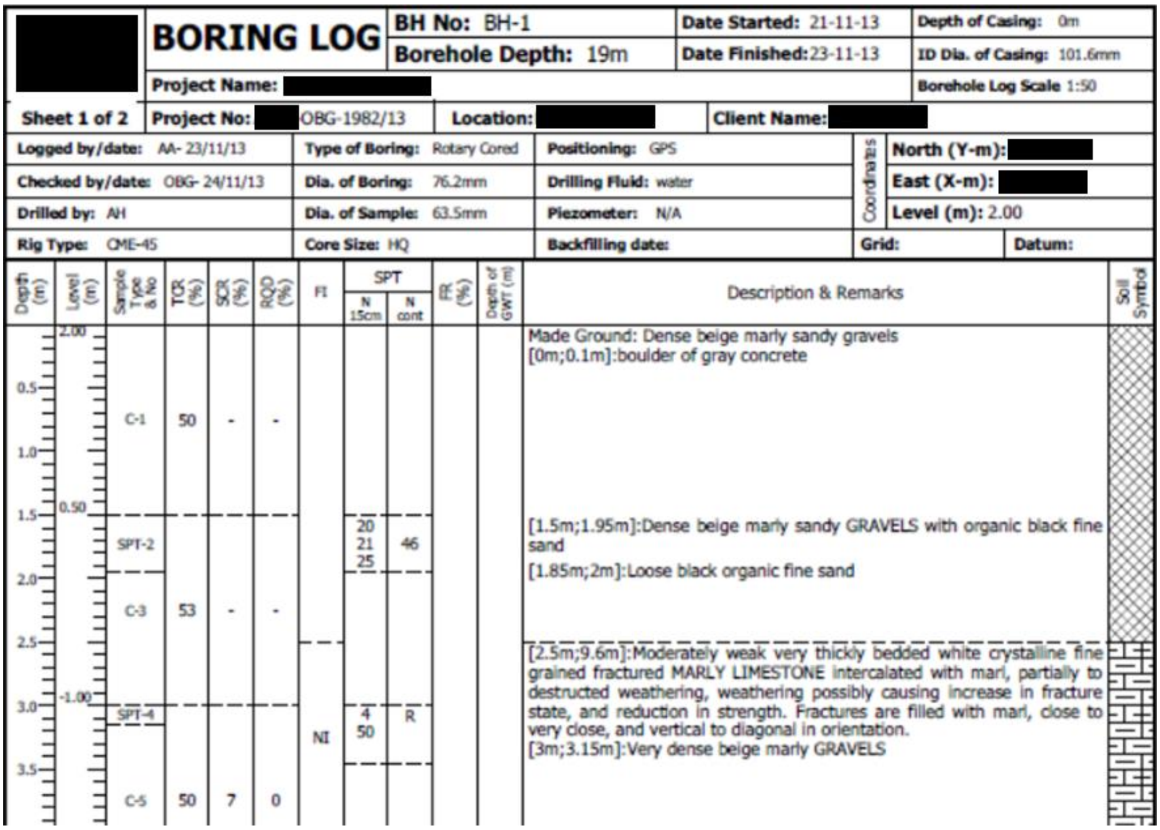


Figure 81: Part of a boring log of a borehole

Table 15- Direct Shear Test of Soils under Consolidated Drained Conditions

Borehole No	Sample Depth (m)	Sample Depth (m, MSL)	C (kPa)	ϕ (°)	Layer	Description	Fines (%)
3	4.4	1.3	17.88	38.2	MG	-	11.3

Table 16- Point load Strength Index of Rock (1 of 2)

BH#	Sample Depth (m, EGL)	Z (m, MSL)	$Is_{(50)}$ (MN/m²)
BH-1	4.2	2.034	0.41
	8.2	-1.966	1.46
	12.4	-6.166	3.11
	15.5	-9.266	0.95

Figure 82: Laboratory test results from the geotechnical investigation report

5.2 Project general observations

Before confirming the model functionality it was important to look at the big picture of the project and analyze its context and see how this work would have added value to the project under study. All data about the project was collected and analyzed. Photos from the project were collected and older files were explored.

The project history was not very homogeneous in terms of schedule and work. During the exploration of old files retrieved from the project, it was found that the project was previously worked on and geotechnical investigations works had been done on the land seven years before the execution of the project. It was found borehole logs for seven boreholes and a geotechnical investigation report with sections of the project subsurface layers dating to 2005 (see fig. 83), and another log for three exploratory boreholes in the plot in 2010 (see fig. 84), made by another contractor.

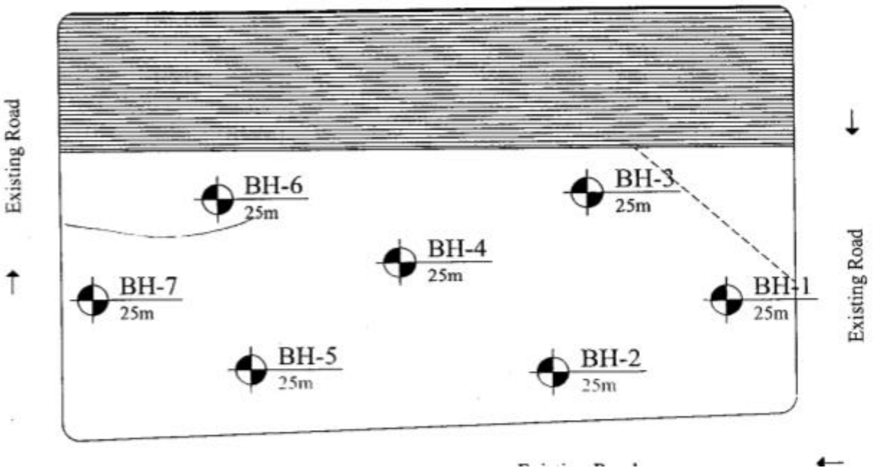


Figure 83: Boreholes done on the plot by a previous contractor in 2005

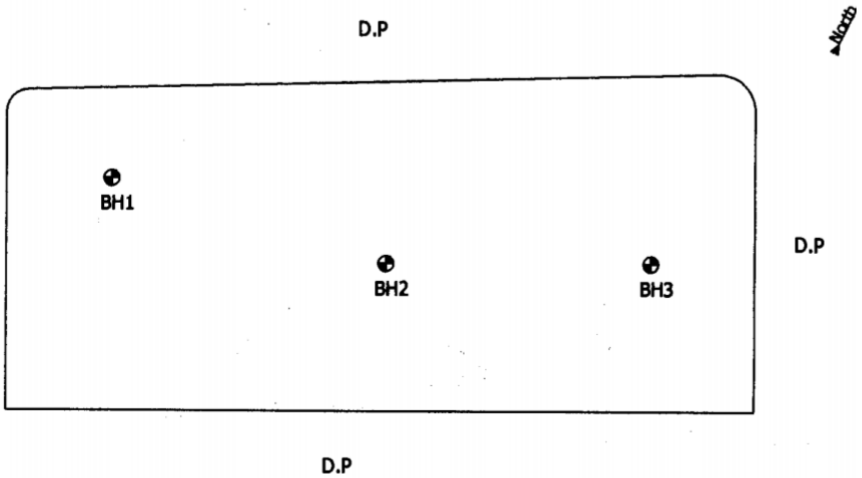


Figure 84: Boreholes done on the plot by a previous contractor in 2010

This finding means that the same land has had 2 different companies performing the same kind of works at different times, and it was noticed that the new geotechnical investigation report did not mention any data collected from the previous reports. This signifies a huge amount of time and effort made for geotechnical works that could have been significantly decreased if the old data was put to use and if there was a standardized work methodology that ensures data saving and re-use in construction projects.

The most recent boreholes' locations could have been changed to have a better and more detailed geotechnical report since the data would be much richer. The boreholes made by the first and second companies were set in one plan, defined by three phases: phase 1 for boreholes done in 2005, phase 2 for boreholes done in 2010, and phase 3 for borehole done in 2012/13. It was proposed new locations for the boreholes made in the last phase that could have made the engineers more informed about the subsurface layers they have in the project plot, and would have given a richer final report that has all the data collected from this site regardless of who did the work and when did they perform it (see fig. 85). It also could have allowed for a fewer number of boreholes if as per the previous data it was not found necessary, for example, if the data shows a very uniform type of subsurface layers in the whole plot, the engineers can opt for only one or two new boreholes to confirm the results.

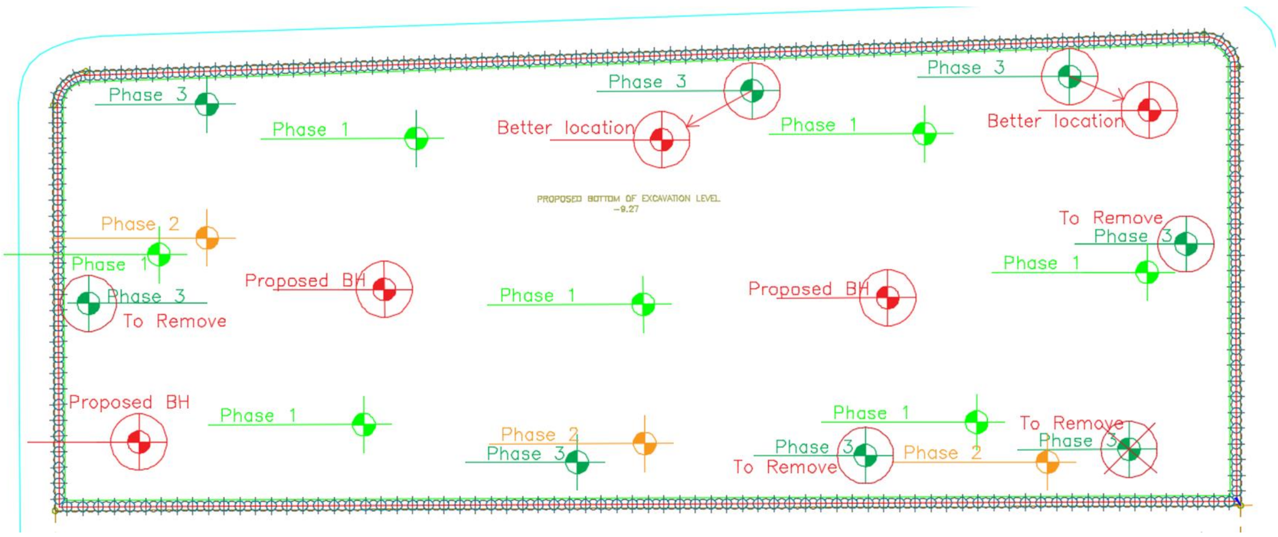


Figure 85: Boreholes executed on the plot in different phases and proposed boreholes' locations for the last phase executed

Further study of the project revealed that the project has had a significant delay in the excavation phase after the piles where done, due to the discovery of underground old structures that the municipality had to investigate and send special teams of archeologists to uncover the structure in a way that preserves them, then study them and understand the era they belong to (see fig. 86). This caused the site to close for more than a month and only after the approval of the municipality the project was permitted to continue, realizing that these structures are recent.

Figure 86: Old structures found during the excavation phase

The data available at hand from old geotechnical reports were analyzed more deeply to have a better understanding of how data preservation and reuse of data could have mitigated this problem or at least give the company a warning that they might encounter difficulties or unexpected structures in the plot. It is worth mentioning that all the most recent boreholes executed on the plot did not have any signs of the existing structures, however, looking at the old borehole logs of the older company revealed an interesting find.

The log of borehole number four which lies in the middle of the plot had a concrete layer in it from depth -6 m to -10.5 m (see fig. 87). This also showed in the sections made for the plot, where it showed the presence of a concrete layer also at the mentioned depths (see fig. 88).

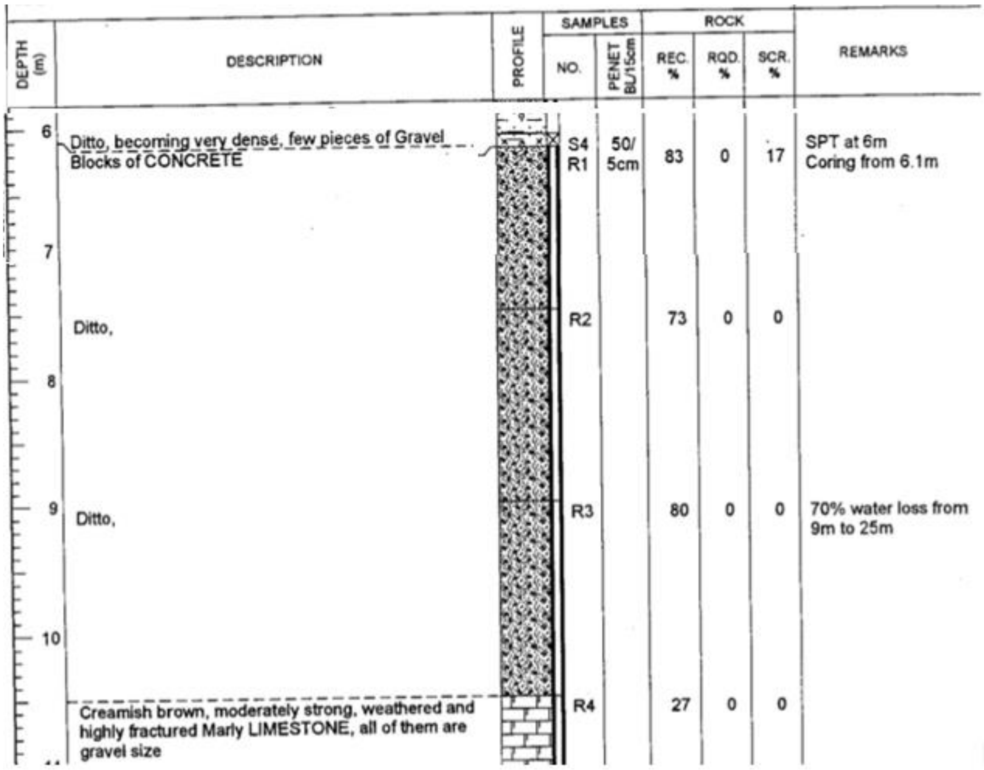


Figure 87: Data from old borehole log showing concrete layer

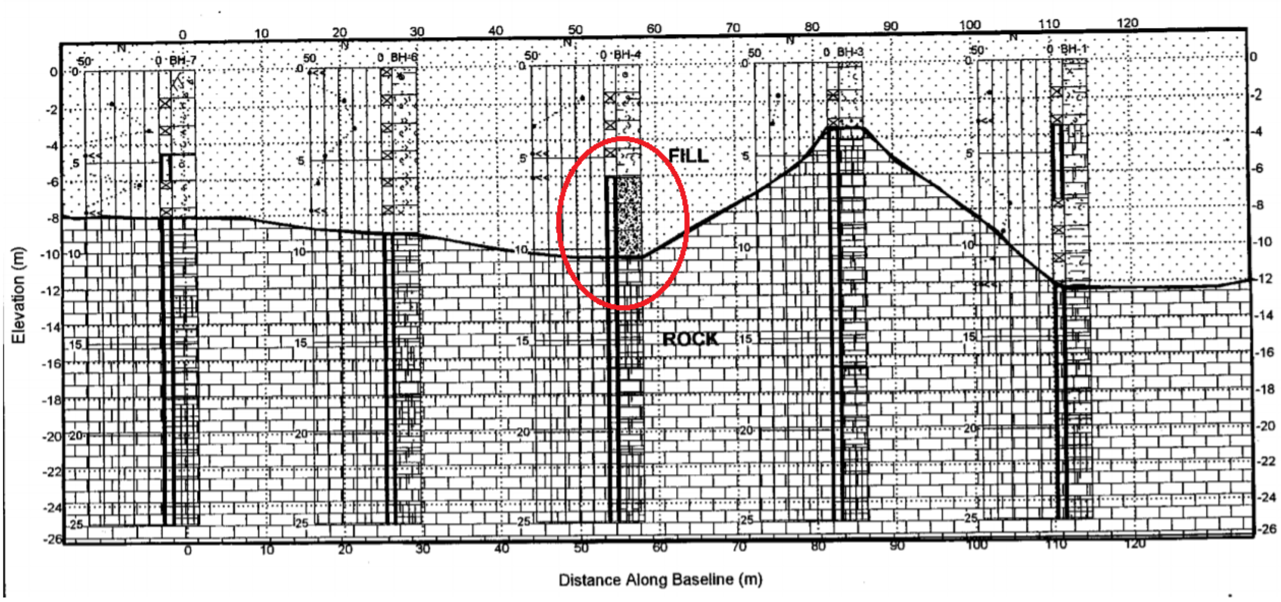


Figure 88: Data from old borehole section view showing concrete layer

Furthermore, It was discovered that existing utilities caused some issues during the phase of casting the secant piles. A rainwater line that was intruding into the plot was exposed partially during the drilling of a pile. The problem was that it was only discovered during the casting of the concrete phase, where the concrete started to show on the outer part of the rainwater pipe where exists a rainwater drain. This incident caused a huge amount of money to be fined to the project by the municipality for damage repair (see fig. 89).

Figure 89: Rainwater drain line on the edge of the plot

Having an overlook on the project, it is possible to deduce that the preservation and reuse of geotechnical data in the context of construction during the first phases of this project could have held large benefits to it. If this project has been executed using the BIM methodology since the beginning, time and money could have been saved and risks could have been reduced. Also, it is important to note that if it was considered in this project that old structures and utilities were to be added to the BIM model, it could also have helped mitigate risks and delays throughout the project lifecycle.

5.3 The BIM model

After analyzing the context of the project and understanding the issues that were faced, it was time to go to an application of the BIM approach to the geotechnical data that is available from the project. Hence, it was used the most recent borehole data available, from phase 3 of the year 2012/13, to be an example of using geotechnical data in a BIM context.

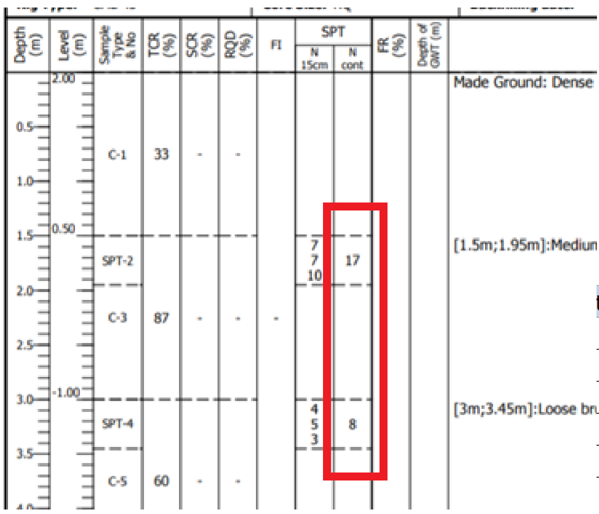
The first step in the work was to input all the data collected from the geotechnical investigation report in the borehole excel sheet created which is based on the borehole PDT and for use with the scripting program. Each borehole was analyzed and the borehole layers were defined as per the readings in the borehole logs, and the layer distribution for the boreholes was set accordingly. In this way, in the excel sheet, the depths of each layer in each borehole was defined and the layers that did not exist in some boreholes were given zero thickness (see fig 90).

C	D	E	F	G
Northing	BHLevel	DepthTop	DepthBase	LayerNumber
0.0	6.23	0	-2	1
0.0	6.23	-2	-2	2
0.0	6.23	-2	-14.5	3
0.0	6.23	-14.5	-15.5	4
0.0	6.23	-15.5	-19	5
0.0	6.23	-19	-19	6
0.0	6.23	-19	-19	7
-1.2	5.96	0	-3	1
-1.2	5.96	-3	-6.5	2
-1.2	5.96	-6.5	-12.7	3
-1.2	5.96	-12.7	-14.8	4

Figure 90: Zero thickness on non-existing layers in the borehole excel sheet

During the recording of data, it was noticed that some layers like Limestone or Manmade ground can have more than one in-situ or laboratory test. For example, the same layer can have three different SPT tests, and in the model, these three tests have one spot to be recorded on, which is in the row that belongs to that layer. Hence when it was encountered more than one test for the same layer, it was necessary to find a way that ensures all the data in that layer is preserved.

Accordingly, it was proposed that the data would be recorded in a vector form in the PDT and the borehole excel sheet (see fig. 91). In figure 84 it can be seen that the SPT data was translated into the borehole excel sheet in a vector form stating the depth of the test and the perspective value. The same recording methodology would be carried out through the PDT and borehole excel sheet on all the laboratory and in-situ tests that represent more than one result in the same layer.



tyVerticalDirection	SPTNValue	SPTCorrectedNValue
n/a	n/a	n/a
n/a	[1.5, 17]; [3, 8]	n/a
n/a	n/a	n/a
n/a	n/a	n/a
n/a	n/a	n/a
n/a	n/a	n/a

Figure 91: SPT results in the same layer (left), and SPT results in borehole excel sheet (right)

It is also important to note that since wanting to view the model in the local coordinates of Revit, all the borehole coordinates were translated so that the first borehole "BH1" would be the origin of the model with coordinates zero for X and Y axis (see fig. 92). This translation made it simpler to handle the model and view it in Revit, hence it is advised to be performed. However, after the model is in Revit, it is easy to move it to another desired location if necessary.

Easting	Northing	BHLevel	DepthTop	DepthBase
-337532.7	-27129.4	6.23	0	-2
-337532.7	-27129.4	6.23	-2	-2
-337532.7	-27129.4	6.23	-2	-14.5
-337532.7	-27129.4	6.23	-14.5	-15.5
-337532.7	-27129.4	6.23	-15.5	-19
-337532.7	-27129.4	6.23	-19	-19
-337532.7	-27129.4	6.23	-19	-19
-337561	-27130.6	5.96	0	-3
-337561	-27130.6	5.96	-3	-6.5
-337561	-27130.6	5.96	-6.5	-12.7
-337561	-27130.6	5.96	-12.7	-14.8
-337561	-27130.6	5.96	-14.8	-19

Easting	Northing	BHLevel	DepthTop	DepthBase
0.0	0.0	6.23	0	-2
0.0	0.0	6.23	-2	-2
0.0	0.0	6.23	-2	-14.5
0.0	0.0	6.23	-14.5	-15.5
0.0	0.0	6.23	-15.5	-19.1
0.0	0.0	6.23	-19.1	-19.1
0.0	0.0	6.23	-19.1	-19.1
-28.3	-1.2	5.96	0	-3
-28.3	-1.2	5.96	-3	-6.5
-28.3	-1.2	5.96	-6.5	-12.7
-28.3	-1.2	5.96	-12.7	-14.8
-28.3	-1.2	5.96	-14.8	-19

Figure 92: Translation of global coordinates to local coordinates in borehole excel sheet

After filling all the necessary data in the borehole excel sheet, the next step was in Revit to prepare the model to run the program. First, the borehole family created was imported into the model, then the units of the model were set to be the same as the data in the excel sheet. Then Dynamo was launched and the program was loaded. Then the correct attachment was set in the node that pulls data from excel files and the program was run to see the resulting model (see fig. 93).

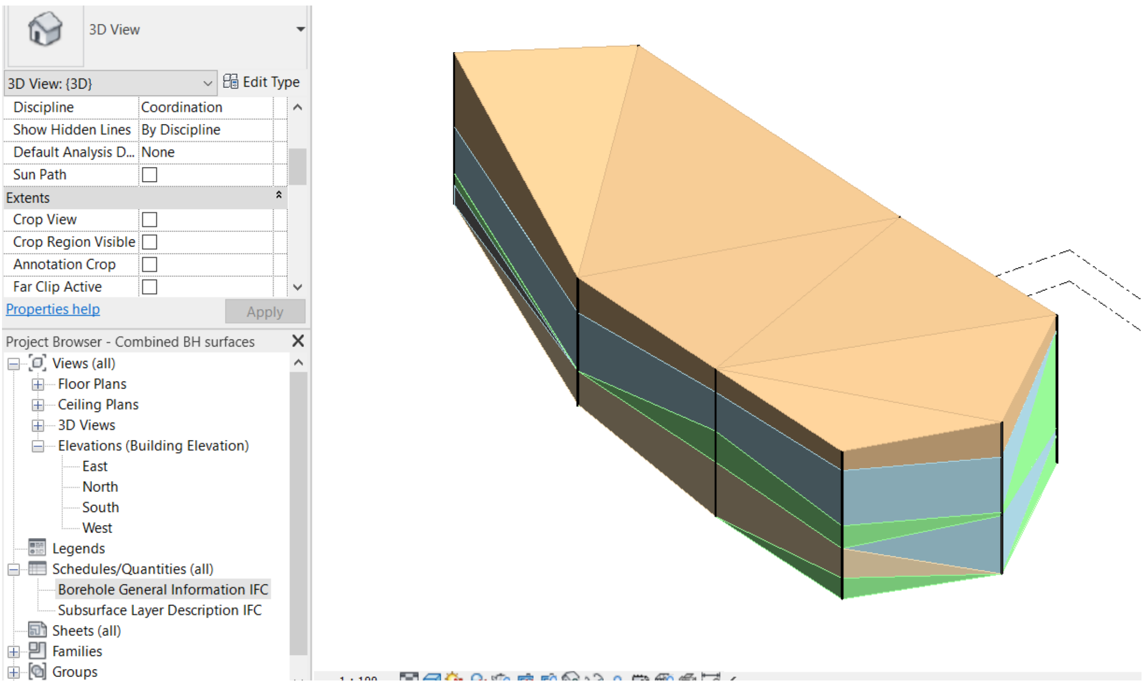


Figure 93: Result of running modelling program created on borehole data of the project

When analyzing the model it was noticed that all boreholes elements were modelled and all the data from the excel sheet was populated in the borehole elements in the parameters part in the properties section (see fig. 94). The subsurface layers modelled were visible, as per the color-coding defined in the script, and the parameter that defines each layer was also visible in the properties part (see fig. 95).

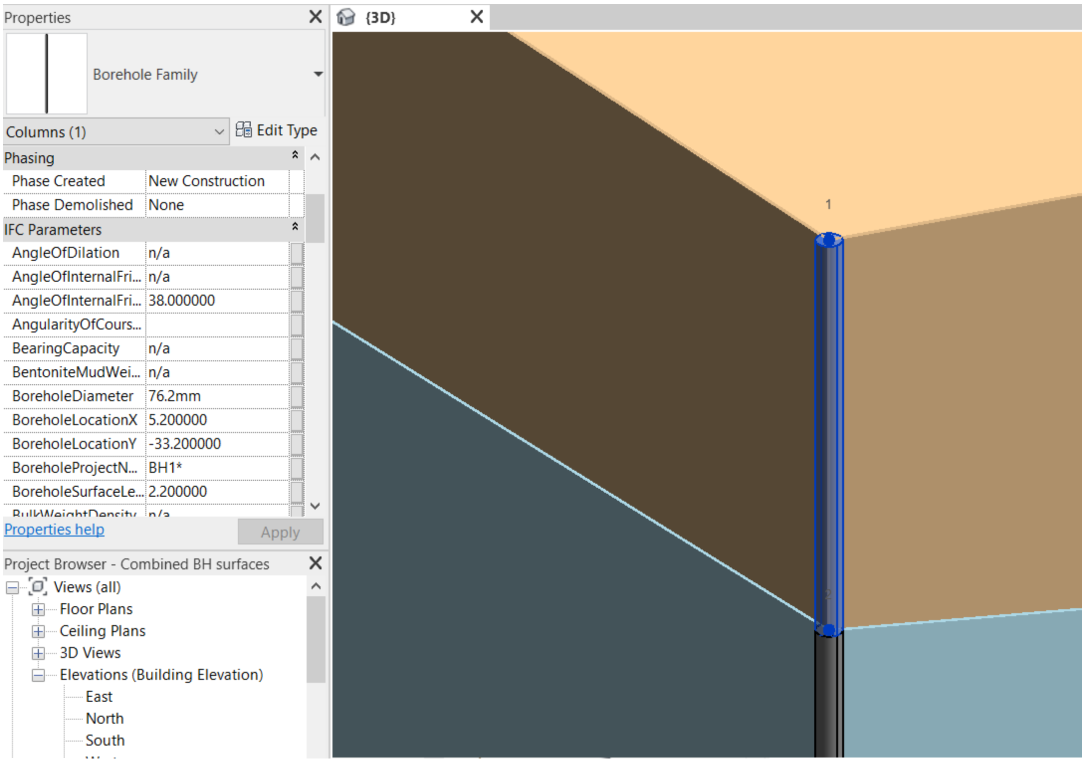


Figure 94: Borehole element in Revit with parameters populated with data in properties

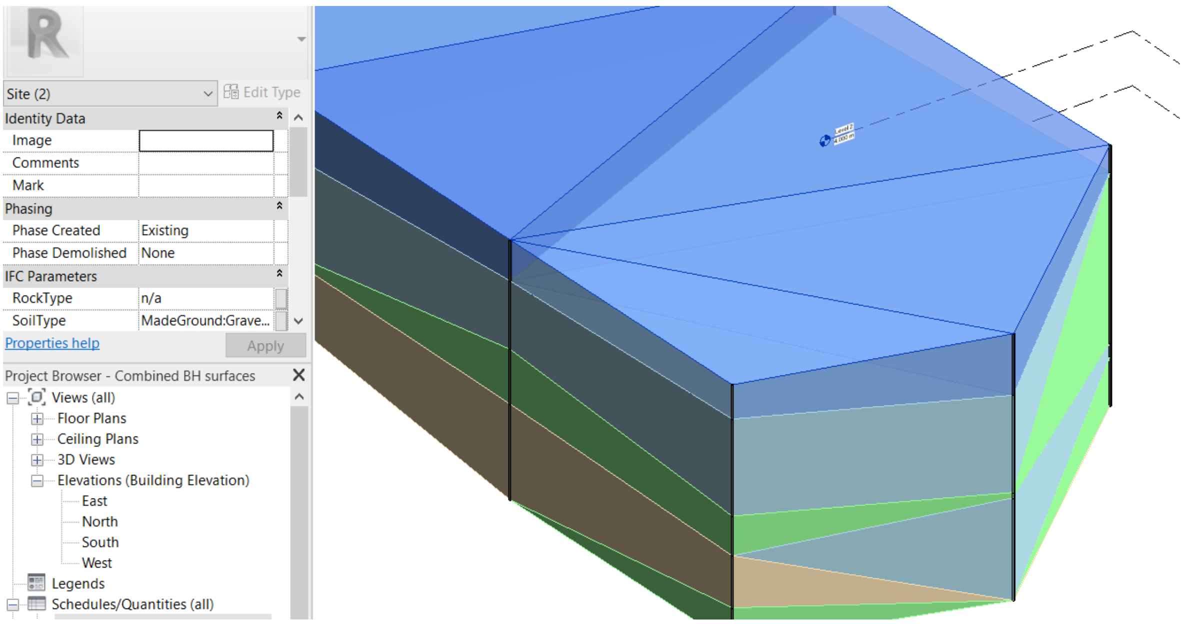


Figure 95: Subsurface layer element in Revit with parameters populated with data in properties

To save the model in IFC format, the same procedure mentioned earlier was followed and the IFC properties were customized, and schedules were uploaded to Revit. After all the settings were set as per requirements the model was exported in IFC format. Then it was opened it in another platform, BIM Vision, to see the results and confirm the success of the export. The model was exported and the boreholes and subsurface layers were successfully loaded (see fig. 96).

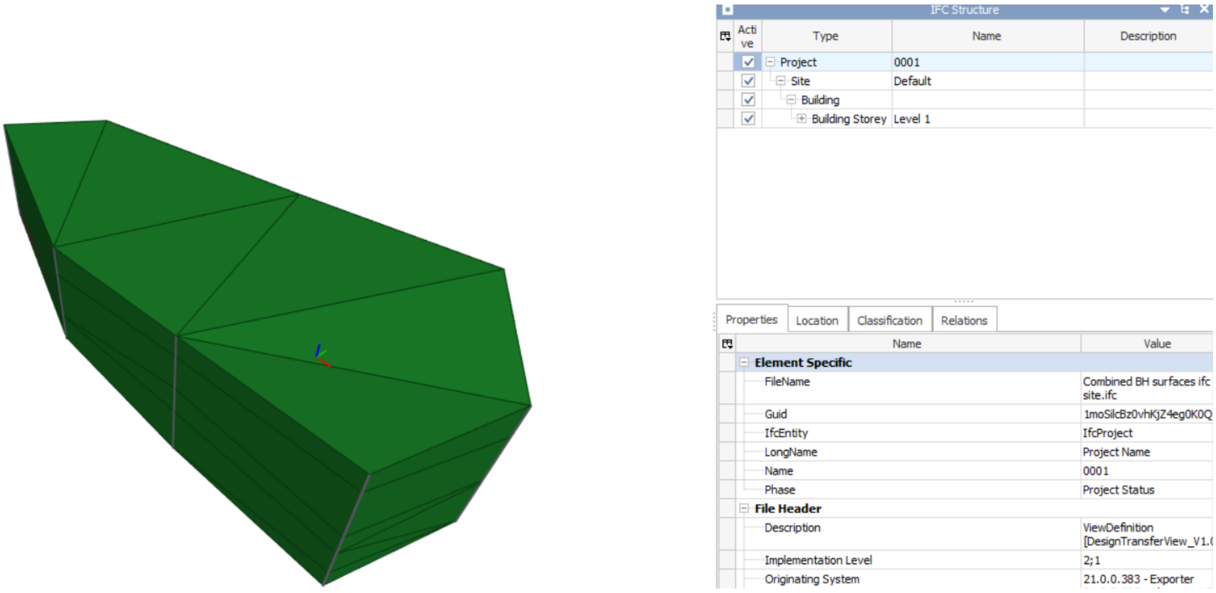


Figure 96: Boreholes and subsurface layers in BIM Vision open from IFC file

A borehole was selected to confirm that the parameters are present in its properties. It was possible to confirm the migration of all the element parameters and separated as per the group titles recorded in the schedules of the parameters in Revit (see fig. 97). Then a subsurface level was selected to confirm the presence of the parameter that describes the layer material, and it was also possible to confirm the presence of the parameters SoilType and RockType in the element properties (see fig. 98).

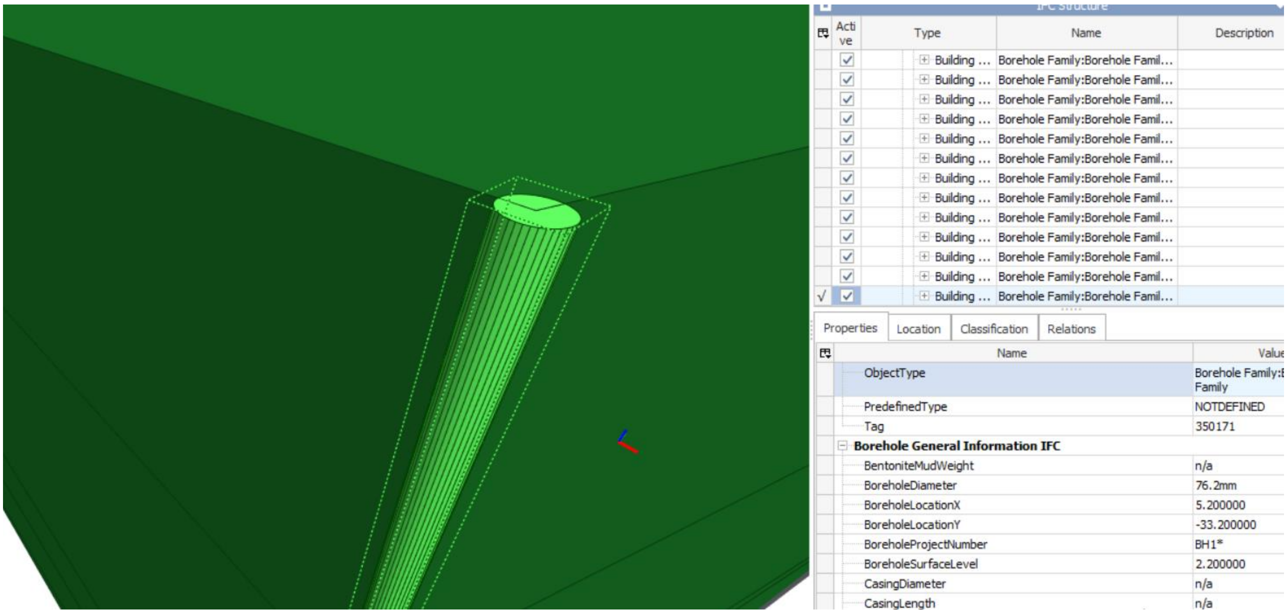


Figure 97: Borehole element in the IFC model with exported parameters in properties

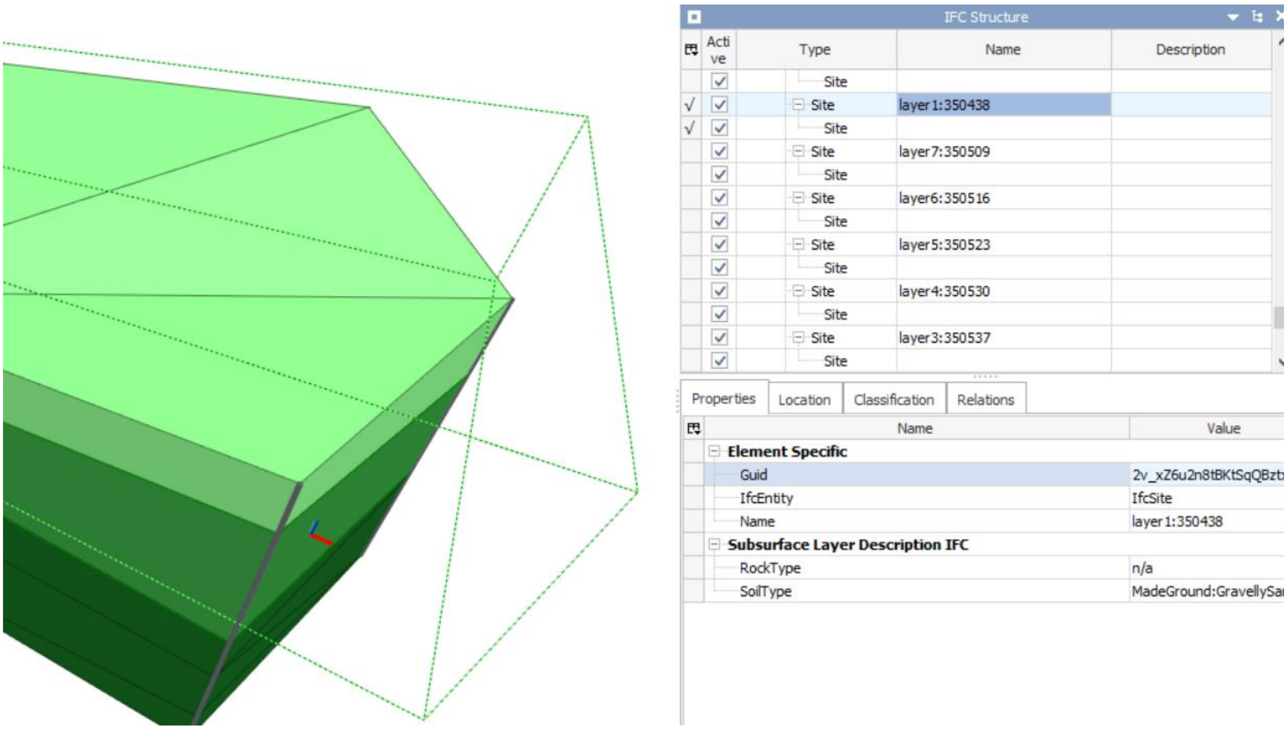


Figure 98: Subsurface element in the IFC model with exported parameters in properties

After confirming that the modelling process is successful, a section in the model that was created earlier was performed in a similar location than the one made in figure 88. Then it was added what could have been shown in the section where data indicating the presence of concrete in the middle of the plot was observed (see fig. 99), just to visually illustrate how seeing that data could have helped users to have more awareness of the issues present on the plot if the work was done using the BIM approach since the beginning of the project.

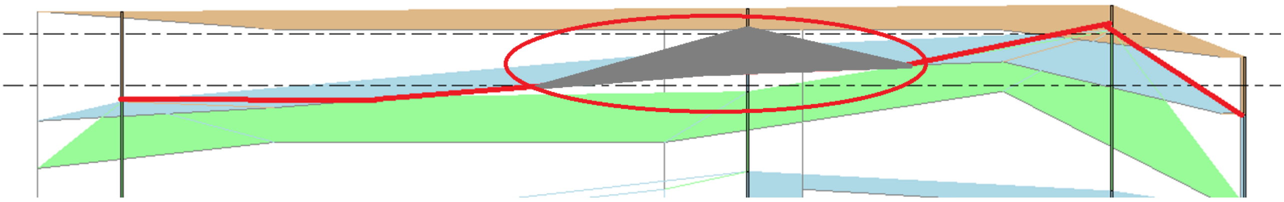


Figure 99: Demonstration of how the concrete layer would have appeared in the BIM 3D model with a red line showing the start of the first rock layer

6 CONCLUSION

6.1 General conclusions

In this work, it was intended to propose and implement a BIM approach toward handling geotechnical data. The goals were fulfilled by harvesting the benefits of data standardization on borehole data and visual scripting tools in the BIM platform to create a program to use geotechnical data from boreholes for 3D modelling of semantically rich objects. The interoperability of the model was also a subject of interest, which was addressed by using open data formats. It was also planned to make a case study to test the program and analyse the context of the project and carry out conclusions.

Regarding the standardization of data, the created PDT is a start toward standardizing how all subsurface data can be recorded digitally. It was shown in the case study done how it was possible to use this data for archiving, and demonstrate its usefulness in the future. It was noticed how the processing of data from the PDT to the BIM platform was a seamless process after the data was recorded. This is one of the goals of standardization of data, where it will improve the way data is handled and it will help ensure that the geotechnical elements modelled, like boreholes (in the case of this dissertation), always have all the necessary data to recreate a model or to simply use the saved data for any purpose in a project lifecycle. This work was limited to borehole elements, but it is a positive step to show that this way of working is successful in helping in preserving data and it indicates that if implemented in other subsurface elements it can add value.

Concerning the use of visual scripting tools in the BIM platform to improve how geotechnical data is handled, a brief discussion can be held in the following sentences. A program that uses geotechnical data from boreholes to model the boreholes and the subsurface elements and preserve their data was created. It was seen through the results of the case study how the data from the PDT-based excel sheet was enough to be able to model the boreholes and include all the data as parameters in the borehole elements. It was also seen that it was possible to create a 3D model of the subsurface with the parameters describing the layers as well.

Regarding the issue of the interoperability of the model, the approach of this dissertation consisted in using open data formats for the preservation of data. Using the IFC export option in Revit, it was possible to export the model elements, boreholes, and subsurface layers, including all the parameters that were attached with them in IFC format. It was seen that it was possible to open the model and view all the exported data in another program, hence confirming the export to IFC was successful.

The case study that was made was a positive confirmation of the previous goals concerning modelling, and the results of the work were satisfactory. From the general perspective of the case study, it was seen that the project had indeed suffered major delays and additional costs because of the unpredictability of the subsurface, which confirms the points made in the literature review. It was also possible to understand from the history of the project that better use of geotechnical data can be a factor in reducing risks in projects.

6.2 Future recommendations

The work done represents a small contribution to the geotechnical engineering community. The possibility of using the latest tools in the BIM platform to create an efficient tool that allows the transfer of geotechnical data from ending up as hardcopies in an archive, to a 3D digital model that can be shared between multiple stakeholders and used in the future without any loss of data is just a glimpse of what can be achieved if the full potential of the BIM tools and methodologies were exploited. The perspective of geotechnical engineers and other stakeholders who contribute to creating the geotechnical investigation report was used to find a way for the data to be processed in the BIM approach.

The program created was tested on data adapted from a real case and was used in an academic framework to be tested on the specific situation presented herein. For real case situations, further development of the program would be needed as they would present further challenges. The connection between the PDT created for the user interface and the Dynamo script is also a step that requires development in the future to improve the process of data entry into the program that transforms this data into the BIM platform. The modelling of the underground water layer using data from inclinometers on projects or from borehole water level measurements and the addition of voids found in boreholes are also a path that needs further improving and developing.

3D geological models have great potential to evolve, with so much data from so many sources that can be added to the subsurface models. Data like borehole descriptions, hydrological data, historical and archaeological data, Geotechnical tests, topography data, geological maps, construction drawings, mine plans, and any subsurface data related to man-made structures are all possible data resources to be inputted in the geotechnical 3D BIM model (Schocker et al., 2017) These data sources all need to be collected, analysed, put in digital forms and standardized before they can be used in a 3D model, and this creates a big array of choices for future studies and research to develop and improve over this work.

REFERENCES

AGS, 2012. Association of Geotechnical and Geoenvironmental Specialists. Retrieved 10 June 2020 from http://www.ags.org.uk/datatransferv4/intro.php#AGS4

Arnous, M.O. 2013. Geotechnical site investigations for possible urban extensions at Suez city, Egypt using GIS. Arabian Journal of Geosciences 6(5): 1349–1369.

Atkins, W. S. 2006. The risk to third parties from bored tunneling in soft ground. Research report 453. Health and Safety Executive: 1-78. Sudbury, UK.

Autodesk, 2018. Revit IFC manual. Retrieved July 14 2020 from https://damassets.autodesk.net/content/dam/autodesk/draftr/2528/180213_IFC_Handbuch.pdf

Autodesk. Gaining Deep Competitive Advantage. Retrieved 10 June 2020 from https://www.autodesk.com/solutions/bim/hub/stantec-gains-deep-competitive-advantage-with-bim

Autodesk. Infrastructure innovators use VR games to streamline Scandinavian tunnel design. Retrieved July 14 2020 from https://www.autodesk.co.uk/customer-stories/norconsult-vr-gamification

Azhar, S. & Nadeem, A. Mok, J. & Leung, B. 2008. Building Information Modeling (BIM): a new paradigm for visual interactive modeling and simulation for construction projects. Proc. Conference: First International Conference on Construction in Developing Countries, At Karachi, Pakistan, 4-5 August 2008.

Bentley, 2020. An Overview of Generative Components. Retrieved July 14 2020 from https://communities.bentley.com/products/products_generativecomponents/w/generative_components_community_wiki

Bentley, 2020. Data entry Tutorial for gINT. Retrieved 14 July 2020 from https://communities.bentley.com/products/geotechnical1/m/mediagallery/271336

Bentley, 2020. SVDESIGNER, 3D Geotechnical Conceptual Modeler. Retrieved July 15 2020 from https://www.bentley.com/en/products/product-line/geotechnical-engineering-software/svdesigner

Berdigylyjov, M., & Popa, H., 2019. The implementation and role of geotechnical data in BIM process. In M.C. Balan, F. Bode, C. Croitoru, A. Dogeanu, A. Georgescu, C. Georgescu, I. Nastase, M. Sandu (eds.), E3S Web of Conferences 2nd Symposium on OpenFOAM in Wind Energy; Proc., 85, Colorado, 19-21 May 2014. doi:10.1051/e3sconf/20198508009

Bew, M. & Richards, M. 2008. BIM Maturity Model. Paper presented at the BuildingSMART Construct IT Autumn 2008 Members' Meeting. Brighton, UK.

BGS, 2020. Geology of Britain viewer. Retrieved July 13 2019 from http://mapapps.bgs.ac.uk/geologyofbritain/home.html?

BGS3D, 2020. British Geological Survey – 3D Geology (BGS3D). Retrieved July 13 2019 from http://mapapps.bgs.ac.uk/geologyofbritain3d/

BIMForum, 2019. Level of Development Specification. Retrieved May 8 2020 from https://bimforum.org/lod/

Borrmann, A., Kolbe, T. H., Donaubauer, A., Steuer, H., Jubierre, J. R. & Flurl, M. 2014. Multi scale geometric semantic modeling of shield tunnels for GIS and BIM applications. Computer-Aided Civil and Infrastructure Engineering 30(4): 263–281.

Boshernitsan, M. & Downes, M. 2004. Visual Programming Languages: A Survey. Report No. UCB/CSD-04-1368. Computer Science Division. University of California, Berkeley, California.

Bradley, A., Li, H., Lark, R. & Dunn, S. 2016. BIM for infrastructure: An overall review and constructor perspective. Automation in Construction 71(2): 139–152. doi:10.1016/j.autcon.2016.08.019

bSDD, 2018. buildingSMART Data Dictionary. Retrieved July 14 2019 from www.buildingsmart.org/users/services/buildingsmart-data-dictionary/

BSI Group, Specification for information management for the capital/delivery phase of construction projects using building information modelling. PAS 1192-2:2013 (2013 version), online. 15 Retrieved 14 April 2020 from https://www.bsigroup.com/en-GB/

buildingSMART, 2018. Phil Jackson on behalf of buildingSMART, Infrastructure Asset Managers BIM Requirements. Retrieved July 10 2019, from www.buildingsmart.org/wp-content/uploads/2018/01/18-01-09-AM-TR1010.pdf

buildingSMART, 2019. IFC4 Reference View. Retrieved 14 July 2020 from https://standards.buildingsmart.org/MVD/RELEASE/IFC4/ADD2_TC1/RV1_2/HTML/schema/views/reference-view/index.htm

BuildingSMART, 2020. IFC inheritance. Retrieved July 14 2020 from https://standards.buildingsmart.org/IFC/RELEASE/IFC4_1/FINAL/HTML/schema/ifcproductextension/lexical/ifcbuildingelement.htm

buildingSMART, 2020. What is openBIM? Retrieved July 14 2020 from https://www.buildingsmart.org/about/openbim/openbim-definition/

Caers, J. 2011. Modeling Uncertainty in the Earth Sciences. Wiley-Blackwell, Chichester, West Sussex, UK.

CEN/TC 442, 2018. European Committee for Standardization, Building Information Modelling Standards. Retrieved July 14 2020 from https://standards.cen.eu/dyn/www/f?p=204:32:0::::FSP_ORG_ID,FSP_LANG_ID:1991542,25&cs=1085D2CA41E34A1C2DA860E5234AA5A97

Chang, Y.S. & Park, H.D. 2004. Development of a web-based geographic information system for the management of borehole and geological data. Computers & Geosciences 30(8): 887–897.

Cherkaoui H. 2017. A History of BIM. Retrieved July 14 2020 from https://www.letsbuild.com/blog/a-history-of-bim

Child, P., Grice, C. & Chandler, R. 2014. The geotechnical data journey— How the way we view data is being transformed. Information Technology in Geo-Engineering 3: 83-88. doi:10.3233/978-1-61499-417-6-83

Choi, Y., Yoon, S.Y. & Park, H.D. 2009. Tunneling analyst: a 3D GIS extension for rock mass classification and fault zone analysis in tunneling. Computers & Geosciences 35(6): 1322–1333.

CIBSE, 2017. CIBSE, Building Information Modelling. Retrieved July 5, 2019, from www.cibse.org/knowledge/bim-building-information-modelling/product-data-templates

Clarke, S.M., 2004. Confidence in geological interpretation: a methodology for evaluating uncertainty in common two and three-dimensional representations of subsurface geology. British Geological Survey Internal Report IR/04/164, UK: 29. Retrieved July 21 2020 from http://nora.nerc.ac.uk/id/eprint/509482

Classon F., 2018. Use point clouds for preliminary and detailed infrastructure design. Retrieved May 7 2020 from https://knowledge.autodesk.com/support/civil-3d/getting-started/caas/simplecontent/content/infrastructure-E2-80-94data-preparation-E2-80-94point-cloud-processing-for-infrastructure-projects.html

CRAFTAI. The maturity of visual programming. Retrieved July 15 2020, from http://www.craft.ai/blog/the-maturity-of-visual-programming

Culshaw, M.G. 2005. From concept towards reality: developing the attributed 3D geological model of the shallow subsurface. Quarterly Journal of Engineering Geology and Hydrogeology 38, 231–284.

Dave, B., Boddy, S. & Koskela, L. Y. 2013. Challenges and opportunities in implementing lean and BIM on an infrastructure project. In 21st Annual Conf. of the Int. Group for Lean Construction (IGLC), International Group for Lean Construction (IGLC), 21 July 2013. Berkeley: CA. Retrieved 21 July 2020, from https://iglcstorage.blob.core.windows.net/papers/attachment-58377480-00ef-401b-b904-38a4346dfd88.pdf

Designingbuildings, 2019. Level of detail for BIM. Retrieved May 28 2020 from https://www.designingbuildings.co.uk/wiki/Level_of_detail_for_BIM

Dong-ping, D., Zhao, L. & Li, L. (2014). Limit equilibrium slope stability analysis using the nonlinear strength failure criterion. Canadian Geotechnical Journal 52(5): 563-576. doi:. 10.1139/cgj-2014-0111

DINO, (2020). Data en Informatie van de Nederlandse Ondergrond (DINO). Retrieved May 25 2020 from www.dinoloket.nl/

DynamoPrimer, 2019. Retrieved July 13 2019 from www.primer.dynamobim.org/en/index.html

Eastman, C. M., Jeong, Y.-S., Sacks, R. & Kaner, I. 2009. Exchange model and exchange object concepts for implementation of national BIM standards. Journal of Computing in Civil Engineering 24(1): 25–34. doi:10.1061/(asce)0887-3801(2010)24:1(25)

Eastman, C., Teicholz, P., Sacks, R. & Liston, K. 2008. BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. New York: John Wiley and Sons.

Emmeitalia. Manual Drafting Table. Retrieved May 10 2020 from https://www.emmeitalia.com/en/drafting-tables/

Fenton, G.A., Griffiths, D.V. 2008. Risk Assessment in Geotechnical Engineering. John Wiley & Sons: New Jersey.

Fernandes, L., Azenha M. & Couto, P. 2015. An integrated model for simulation of construction phasing of arch concrete dams. Retrieved 10 May 2020 from http://hdl.handle.net/1822/40572

Fernandez, S. 2019. Structural Columns, Retrieved July 14 2020 from https://www.modelical.com/en/gdocs/structural-columns-modeling-and-configuration-in-revit/

Fine, 2019. Create 3D Subsoil Model from Geological Cross Sections in GEO5 Stratigraphy. Retrieved May 15 2020 from https://www.finesoftware.eu/video-tutorials/163/create-3d-subsoil-model-from-geological-cross-sections-in-geo5-stratigraphy/

Fine, 2020. Compatibility of Boreholes. Retrieved 14 July 2020 from https://www.finesoftware.eu/help/geo5/en/compatibility-of-boreholes-01/

Fookes, P.G. 1997. Geology for engineers: the geological model, prediction and performance. The first Glossop lecture. Quarterly Journal of Engineering Geology and Hydrogeology 30(4): 293–424. doi.org/10.1144/GSL.QJEG.1997.030.P4.02

Lee, G. & Borrmann, A. 2020. BIM policy and management. Construction Management and Economic 38(5): 413-419. doi: 10.1080/01446193.2020.1726979

Gedeon, G. 2014. Design of Pile Foundations, Civil Engineering Project I (Civil 597), University of Calgary: Canada. https://www.cedengineering.com/courses/design-of-pile-foundations

Gondar, J. Pinto A. & Fartaria C. 2019. The use of BIM technology in geotechnical engineering. In Icelandic Geotechnical Society (eds.), 17th European conference on soil mechanics and geotechnical engineering, Reykjavik, Iceland, 1-6 September 2019. doi: 10.32075/17ECSMGE-2019-0530

Grover, K. & Sridharan R. 2016. Point Cloud Extraction for Infrastructure Projects. Retrieved May 6 2020 from https://www.autodesk.com/autodesk-university/class/Point-Cloud-Extraction-Infrastructure-Projects-2016

Hack, H.R.G.K., 1997. Digital data for engineering geology: disaster or benefit. In European Science Foundation conference: Virtual environments for the Geosciences in Space-time modelling of bounded natural domains; Proceedings, Kerkade, 9-14 December 1997. The Netherlands: Rolduc.

Hack, R., Orlic, B., Ozmutlu, S., Zhu, S. & Rengers, N. 2006. Three and more dimensional modelling in geo-engineering. Bulletin of Engineering Geology and the Environment 65(2): 143–153.

Handa, S. C., Saran, Swami, Ramasamy, G., Rao, A. S. R. & Prakash, B., 1984. Geotechnical Investigations for Foundation Design for Multi-storeyed Building. In The 1st Conference of the International Conference on Case Histories in Geotechnical Engineering; Proceedings, Rolla, 6 May

1984. United States: Missouri. Retrieved July 2020 from https://scholarsmine.mst.edu/icchge/1icchge/1icchge-theme8/5

Heikkila, R., Liukas, J. & Karjalainen, A. 2013. Development and utilization of open information transfer formats in infrastructure sector. In the 30th Int. Symp. on Automation and Robotics in Construction and Mining (ISARC) Held in Conjunction with the 23rd World Mining Congress; Proceedings, Montréal, 1-15 August 2013. Canada: Montréal. doi: 10.22260/ISARC2013/0138

ISO 19650-1, 2018. Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM), Information management using building information modelling, Part 1: Concepts and principles. Retrieved July 21 2020 from https://www.iso.org/obp/ui/#iso:std:iso:19650:-1:ed-1:v1:en

ISO/FDIS 23387, 2020. Building information modeling (BIM), Data templates for construction objects used in the life cycle of any built asset, Concepts and principles. Retrieved June 6 2020 from https://www.iso.org/standard/75403.html ISO/FDIS 23387

Jackson P., 2018. Infrastructure Asset Managers BIM Requirements. Retrieved July 14 2020 from http://www.buildingsmart.org/wp-content/uploads/2018/01/18-01-09-AM-TR1010.pdf

Jia, N., Yang, Z., Xie, M., Mitani, Y. & Tong, J. 2015. Gis-based three-dimensional slope stability analysis considering rainfall infiltration. Bulletin of Engineering Geology and the Environment 74(3): 919–931.

Kensek, K. 2015. Visual programming for building information modeling: Energy and shading analysis case studies. Journal of Green Building 10(4): 28-43. doi: 10.3992/jgb.10.4.28

Keynetix, 2015. AutoCAD Geology Lenses using HoleBASE SI Extension for AutoCAD Civil 3D. Retrieved July 14 2020 from https://www.youtube.com/watch?v=4eMsUiYBhuE

Keynetix, 2019. 3D visualization of boreholes. Retrieved June 14 2019 from https://www.keynetix.com/products/holebase-si-extension-for-autocad-civil-3d/3d-visualization/

Kim, S. & Gultekin-Bicer, P. 2018. An infrastructure for geotechnical building information modeling (BIM). IFCEE 2018: Installation, Testing, and Analysis of Deep Foundations 294: 211-218. doi:10.1061/9780784481578.022

Kramer, M. 2010. Dreidimensionale Visualisierung von ober- und unterirdischen Konstruktionen in DeepCity3D. Presented DeepCity3D, Workshop, 3D-1 Stadt- modelle. Retrieved June 14 2019 from http://www.3d-stadtmodelle.org/3d-stadtmodelle_2010/08_Krae mer_DeepCity3D.pdf

Kubota, S. & Mikami, I. 2011. Data model–centered four-dimensional information management system for road maintenance. Journal of Computing in Civil Engineering 27(5): 497–510.

Lucky M. N., Pasini D. & Lupica Spagnolo S. 2019. IOP Conf. Ser.: Earth Environ. Sci. 296(012053): 1-12. doi:10.1088/1755-1315/296/1/012053

Ma, Z. & Ren, Y. (2017). Integrated application of BIM and GIS: An overview. Procedia Engineering 196: 1072–1079. doi:10.1016/j.proeng.2017.08.064

Martin P., 2008. Géotechnique appliquée au btp [Geotechnics applied to construction]. Paris: Eyrolles.

Marzouk, M. & Abdel-Aty, A. 2012. Maintaining subway infrastructure using BIM. Proc., 2012 Construction Research Congress, ASCE, Reston, VA, 2320–2328.

Mathers, S., Burke, H., Terrington, R., Thorpe, S., Dearden, R., Williamson, J. & Ford, J. 2014. A geological model of London and the themes valley, southeast England. Proceedings of the Geologists' Association 125(4): 373–382.

Mcmanamy R. 2017. Norwegian rail project adopts immersive design for public engagement and buy-in. Retrieved July 14 2020 from https://www.autodesk.com/redshift/immersive-design/

McPartland, R. 2017. BIM dimensions - 3D, 4D, 5D, 6D BIM explained _ NBS. Retrieved July 13, 2019 from www.thenbs.com/knowledge/bim-dimensions-3d-4d-5d-6d-bim-explained

Szygielski, M. & Farrar, J. 2004. Guidelines for Performing Foundation Investigations for Miscellaneous Structures, U.S. Department of the Interior Bureau of Reclamation. Retrieved July 15, 2020 from https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/FndtnInv.pdf

Mignard, C. & Nicolle, C. 2014. Merging BIM and GIS using ontologies application to urban facility management in ACTIVe3D. Computers in Industry 65: 1276–1290. doi:10.1016/j.compind.2014.07.008

Molinos R. 2016. Adaptive Components in Revit. Retrieved July 14 2020 from https://www.modelical.com/en/gdocs/adaptive-components/

Monteiro A. 2016. Visual programming language for creating BIM models with level of development 400. In 4th BIM International Conference 2016 São Paulo, Brazil (September 29 and 30) and Lisbon, Portugal (October 13 and 14).

Morin G. R. 2019. Geotechnical BIM: Applying BIM principles to the subsurface. Retrieved July 14 2020 from https://www.autodesk.com/autodesk-university/article/Geotechnical-BIM-Applying-BIM-Principles-Subsurface-2019

Morin, G., Deaton, S.L., Chandler, R. & Miles, S. 2017. Silvertown Tunnel, London, England—A Case Study Applying BIM Principles to the Geotechnical Process. Geotechnical Frontiers 277: 587-595. doi.org/10.1061/9780784480441.061

Morin, G., Hassall, S. & Chandler, R. 2014. Case study - The real life benefits of Geotechnical Building Information Modelling. Information Technology in Geo-Engineering. In D.G. Toll, H. Zhu, A. Osman, W. Coombs & X. Li (eds.), Proceedings of the 2nd International Conference, Durham, UK, 15 July 2014. doi:10.3233/978-1-61499-417-6-95

MTHojgaard 2016. BIM Manual Civil Works and Infrastructure. Retrieved July 14 2020 from https://mth.com/Knowledge/BIM-Manual-Civil-Works-and-Infrastructure

NBS, 2014. BIM Levels explained. Retrieved July 13, 2020, from https://www.thenbs.com/knowledge/bim-levels-explained

NBS, 2019. BIM object standard. Retrieved July 14 2020 from https://www.thenbs.com/our-tools/nbs-bim-object-standard

NBS, 2019. National BIM Report. Retrieved July 14 2020 from https://www.thenbs.com/knowledge/national-bim-report-2019

NBS. 2017. What are BIM objects? Retrieved June 9, 2020, from https://www.thenbs.com/knowledge/what-are-bim-objects

NBS. 2017. What is a federated Building Information Model? | NBS. Retrieved June 9, 2020, from https://www.thenbs.com/knowledge/what-is-a-federated-building-information-model

Nielsen, A. K. & Madsen, S. 2010. Structural modelling and analysis using BIM tools. Master's Thesis Civil Engineering. Aslborg, Aslborg University.

Osello, A., Rapetti, N. & Semeraro, F. 2017. BIM Methodology approach to infrastructure design: Case study of Paniga tunnel. IOP Conference Series: Materials Science and Engineering 245(6): 1-9. doi:10.1088/1757-899X/245/6/062052

Parry, S. 2009. Introduction to engineering geology in geotechnical risk management. Quarterly Journal of Engineering Geology and Hydrogeology 42(4):443–444.

Perez-Sanchez, J. C., Mora-García, R. T., Perez-Sanchez, V. R. & Piedecausa-Garcia, B. 2017. From cad to BIM: A new way to understand architecture. WIT Transactions on the Built Environment 169(1): 45–54. doi:10.2495/BIM170051

Plaxis 2018. Plaxis 2D Connect edition V20, tutorial manual. Retrieved July 13 2019 from https://www.plaxis.com/?plaxis_download=2D-1-Tutorial.pdf

Preidel, C. & Borrmann A. 2016 Towards code compliance checking on the basis of a visual programming language Journal of Information Technology in Construction 21(25): 402-421.

RailBaltica, 2019. RB Rail's BIM documentation. Retrieved July 14 2020 from https://www.railbaltica.org/rb-rail-as-bim-documentation/#

Ramanathan, R., Aydilek, A.H. & Tanyu, B.F. 2015. Development of a gis-based failure investigation system for highway soil slopes. Frontiers of Earth Science 9(2):165-178.

Reilly C. 2014. What is Grasshopper? Retrieved July 14 2020 from https://www.lynda.com/Grasshopper-tutorials/What-Grasshopper/174491/194087-4.html

Royse, K.R., Rutter, H.K. & Entwisle, D.C. 2009. Property attribution of 3D geological models in the Thames Gateway, London: new ways of visualising geoscientific information. Bulletin of Engineering Geology and the Environment 68(1): 1–16. doi: 10.1007/s10064-008-0171-0

RSK, 2016. Engineer's quick reference guide for ground investigations. Retrieved July 14 2020 from https://www.scribd.com/document/396144150/Engineer-s-Quick-Reference-Guide-For-Ground-Investigation#

Sabatini P.J., Pass D.G. & Bachus R.C. 1999. Geotechnical Engineering Circular No. 4: Ground Anchors and Anchored Systems. Washington: Federal Highway Admistration. Retrieved from https://www.fhwa.dot.gov/engineering/geotech/pubs/if99015.pdf

Lau, S., Zakaria, R., Aminudin, E., Saar, C., Yusof, A. & Fatihi, C., Wahid, C. 2018. A Review of Application Building Information Modeling (BIM) during Pre-Construction Stage: Retrospective and Future Directions. OP Conf. Ser.: Earth and Environmental Science 143(012050): 1-10. doi :10.1088/1755-1315/143/1/012050

Schall G., Schmalstieg D. & Junghanns S. 2010. VIDENTE - 3D Visualization of underground infrastructure using handheld augmented reality. Geohydroinformatics: Integrating GIS and Water Engineering CRC Press 1-17. Retrieved from http://www.icg.tugraz.at

Scheffer M., Mattern H. & Konig M. 2018. BIM Project Management. In A. Borrmann, M. König, C. Koch, J. Beetz (eds), Building Information Modeling: 235-249. Cham: Springer. https://doi.org/10.1007/978-3-319-92862-3_13

Schokker, J., Sandersen, P., Beer, H., Eriksson, I. & Kallio, H., Kearsey, T. Pfleiderer, S. & Seither, A. (2017). 3D urban subsurface modelling and visualisation - a review of good practices and techniques to ensure optimal use of geological information in urban planning. TU1206 COST Sub-Urban WG2 Report.

Sekse M. & Emborg, J.S. 2019. New study: Virtual reality unlocks savings in complex infrastructure and construction. Retrieved from https://www.cowi.com/insights/virtual-real-may-unlock-savings-in-complex-infrastructure-and-construction

Shimonti P. 2018. BIM adoption around the world: how good are we? Geospatial world. Retreived July 14 2020 from https://www.geospatialworld.net/article/bim-adoption-around-the-world-how-good-are-we/

Staveren, M.V. 2006. Uncertainty and Ground Conditions: a Risk Management Approach. Oxon: Spon Press.

Stavric, M. & Marina, O. 2011. Parametric modeling for advanced architecture. International Journal of Applied Mathematics and Informatics 5(1): 9- 16.

Stylianidis, E., Valari, E., Pagani, A. et al. 2020. Augmented Reality geovisualisation for underground utilities. Journal of Photogrammetry, Remote Sensing and Geoinformation Science 88(1): 173-185. doi.org/10.1007/s41064-020-00108-x

Sutherland I. 1964. Sketchpad a man-machine graphical communication system. Simulation 2(5): 3-20. doi.org/10.1177/003754976400200514

Tawelian, L. R. & Mickovski, S. B. 2016. The implementation of geotechnical data into the BIM process. Procedia Engineering 143 (1): 734–741. doi:10.1016/j.proeng.2016.06.115

Tegtmeier, W., van Oosterom, P.J.M., Zlatanova, S. & Hack, H.R.G.K. 2009. Information management in civil engineering infrastructural development: with focus on geological and geotechnical information. In Proceedings of the ISPRS Work- shop Vol. XXXVIII-3-4/C3 Comm. III/4, IV/8 and IV/5: Academic Track of GeoWeb 2009 Conference. Cityscapes, Vancouver Canada, 27–31 July 2009.

Tegtmeier, W., Zlatanova, S., van Oosterom, P. J. M. & Hack, H. R. G. K. 2014. 3D-GEM: Geo-technical extension towards an integrated 3D information model for infrastructural development. Computers and Geosciences 64: 126–135. doi:10.1016/j.cageo.2013.11.003

Tekla, Software for BIM, Retrieved July 14 2020 from https://www.tekla.com/us/about/webinars/tekla-structural-engineering-analysis-and-design

Teresko, J. 1993. Parametric Technology Corp.: Changing the way products are designed. Industry Week. Industry Week.

Thanh, L.N. & De Smedt, F. 2014. Slope stability analysis using a physically based model: a case study from a luoi district in thua thien-hue province, vietnam. Landslides 11(5): 897–907.

TMR. 2016. Geotechnical logging of Queensland Government. Retrieved July 13 2019 from www.tmr.qld.gov.au/business-industry/Technical-standards-publications/Geotechnical-Borehole-Logging

Toll, D.G., 2007. Geo-engineering data: representation and standardisation. Electronic Journal of Geotechnical Engineering 12: 1-12.

Torbjorn, A. 2017. Tunnel and Infrastructure Modelling with Dynamo and Revit. Retrieved July 13 2019 from https://www.autodesk.com/autodesk-university/class/Tunnel-and-Infrastructure-Modeling-Dynamo-and-Revit-2017

USGS, 2020. Retrieved from https://webapps.usgs.gov/GeoLogLocator/#!/search

vGIS, 2020, July 14. GIS data in Augmented Reality. Retrieved July 14 from https://www.vgis.io/esri-augmented-reality-gis-ar-for-utilities-municipalities-locate-and-municipal-service-companies/

Waterhouse, R. & Philp, D. 2017. National BIM Report. National BIM Library, 1–28.

WSP. 2017. What is BIM? Retrieved from www.thenbs.com/knowledge/what- is-building-information-modelling-bim

Xu, X., Ma, L. & Ding, L. 2014. A framework for BIM-enabled life-cycle information management of construction project. International Journal of Advanced Robotic Systems 11(1): 1–13. doi:10.5772/58445

Yanbing, W., Lixin, W., Wenzhong, S. & Xiaojuan, L. 2006. 3D integral modeling for city surface & subsurface. In A.A. Rahman & S. Zlatanova, (eds), Innovations in 3D Geo Information Systems. Springer Verlag: 95–105. Berlin: Heidelberg.

Yeniceli, S. & Ozcelik, M. 2015. Practical application of 3d visualization using geotechnical database: A case study karsiyaka (Izmir) settlement area (Turkey). Journal of the Indian Society of Remote Sensing 44(1): 129-134.

Zhang, J., Wu, C., Wang, L., Mao, X. & Wu, Y. 2016. The work flow and operational model for geotechnical investigation based on BIM. IEEE Access 4(1): 7500–7508. doi:10.1109/ACCESS.2016.2606158

Zhang, J., Wu, C., Wang, Y., Ma, Y., Wu, Y. & Mao, X. 2018. The BIM-enabled geotechnical information management of a construction project. Computing 100(1): 47–63. doi:10.1007/s00607-017-0571-8