

TOWARDS EFFICIENT BIM USE OF GEOTECHNICAL DATA FROM GEOTECHNICAL INVESTIGATIONS

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SUMMARY: *The benefits of Building Information Modelling (BIM) in the building sector pushed for its use in the geotechnical sector with evident benefits in projects around the world. Standardization, interoperability, and improved data management are some of the benefits of BIM if used on geotechnical data. This work focuses on transforming traditional workflows of handling geotechnical data into a BIM-based workflow that makes geotechnical data available in BIM contexts. For that, a definition of Product Data Template (PDT) for boreholes is proposed. A script is developed using visual programming tools to import data based on PDTs to the BIM platform and translate it into borehole objects. An additional script is used to represent the subsurface layers in 3D. Finally, the interoperability aspects of the information are discussed to ensure proper processes of IFC export/import in this context. Finally, a case study is presented to demonstrate the efficacy of the proposed workflow.*

KEYWORDS: *Building Information Modelling, geotechnical engineering, boreholes, Product Data Templates, visual programming, Industry Foundation Classes.*

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1. INTRODUCTION

Geotechnical information related to underground conditions holds a great value for the construction industry because of the risks of the inherent uncertainty and the existence of unknown structures underground (Tawelian and Mickovski, 2016; Zhang *et al.*, 2016). The process of collecting geotechnical data for geotechnical reports is a heavy workload process (e.g., land surveying, drilling boreholes, collecting site data, laboratory and in-situ tests, among others) that includes the collaboration of multiple stakeholders (geotechnical engineers, geologists, site personnel, among others). This collected geotechnical data is often misused or lost, because of the traditional methods used to handle geotechnical data (Zhang *et al.*, 2016).

The traditional approach in dealing with geotechnical data is characterized by: (i) the linear waterfall processes that make moving back and forth between stages difficult, (ii) the difficulty it presents when dealing with design and information changes because of the need to repeat processes, and (iii) the division of the processes into isolated ones that lead to delays in the data processing. This process results in the misuse of geotechnical data, information silos, and misinterpretation of results (Child *et al.*, 2014). The high risks that come along with the uncertainty of underground conditions and unidentified underground structures can only be mitigated by better management of geotechnical data. That is exactly what the BIM approach can deliver (Berdiglyjov and Popa, 2019; Gondar *et al.*, 2019; Zhang *et al.*, 2018).

Building Information Modelling (BIM) has proven to be a very effective methodology in managing data in the construction industry. Its main benefits lie in the collaborative work between the different stakeholders involved in a project, where essential data is added by all parties involved in the process to every element in the model including geotechnical elements (Eastman *et al.*, 2018).

The unprecedented success of using BIM in the building sector made its way into the infrastructure, with a noticeable increase in research in this area (Sibaii, 2020). Many successes and clear positive impacts were noted in infrastructural projects around the world (Berdiglyjov and Popa, 2019), in integrating Geographic Information Systems (GIS) with BIM (Camila Andrea Sandoval Bustos, 2020; Kim and Gultekin-Bicer, 2018; Noardo *et al.*, 2020), on using BIM processes in geotechnical engineering (Mignard and Nicolle, 2014; Sharafat *et al.*, 2020), and specifically on data from boreholes and geotechnical investigations (Chang and Park, 2004; Gondar *et al.*, 2019; Kim and Gultekin-Bicer, 2018; Morin *et al.*, 2017; Rincón, 2020; Tegtmeier *et al.*, 2014; Zhang *et al.*, 2016). Joint efforts were also noted in online collaboration platforms like the Infrastructure Room of buildingSMART to combine, enhance and develop open standards which enable process and data integration for Infrastructure (buildingSMART, n.d.).

In this context, governments around the world mandated the use of BIM, which pushed for the standardization of processes to address the diversity and the high number of stakeholders involved in the BIM process, which helped ensure that data is used efficiently (Scheffer *et al.*, 2018). The ISO 19650 standards series is one of the significant BIM standards which became very influential and it is being increasingly adopted by projects worldwide (ISO 19650-1, 2018). This standard defines information requirements for the asset and its components through the recently introduced concept of “level of information need”, which is an index of the extent and granularity of information required to avoid both excess and lack of data. This concept can be seen as an evolution of previous systems such as: (i) the UK system of the Levels of Model Definition (LoMD) (BSI, 2013; PAS 1192-2, 2013), which is a combination of graphical “Level of definition (Lod)”, and non-graphical “Level of Information (LoI)” data; (ii) the system forwarded by AIA/BIMForum based on LOD – Level of Development (BIMForum, n.d.).

The methods of BIM in managing data have been developing especially with the emergence of BIM object standards (NBS, 2019; OBOS, 2018), Product Data Templates that set out standardized properties for BIM objects (CIBSE, 2021), and open data formats like Industry Foundation Classes (IFC) that support interoperability of BIM models (buildingSMART, 2020a). Simply spoken, IFC provided the vessels on which data would be transferred between stakeholders, and PDTs provided the content of these vessels. IFC, an open data format standardized by the ISO 16739-1 uses content from data dictionaries based on ISO 12006-3, of which content is organized into data templates and properties according to the standards BS EN ISO 23386 and BS EN ISO (ISO 16739-1, 2018; ISO 23386, 2020; ISO 23387, 2020; prEN ISO 12006-3 rev, n.d.).

The recently introduced developments in the versions IFC4.3 RC1 and IFC4.3 RC2 included new IFC types to accommodate the possibility of having geotechnical underground elements in the IFC model. IFC types like *IfcSolidStratum*, *IfcWaterStratum*, and *IfcVoidStratum* which belong to the *IfcGeotechnicalStratum* by

inheritance are made to represent the concept of an identified discrete solid, water-filled, and air-filled geological feature simultaneously. *IfcBorehole*, *IfcGeomodel*, and *IfcGeoslice* were also introduced belonging to *IfcGeotechnicalAssembly* by inheritance, these types represent the concept of a Linear, volumetric and sectional planar geological and geotechnical model which may be an interpretation but sometimes created directly from ground-penetrating measurements. Moreover, the property sets *Pset_BoreholeCommon*, *Pset_solidStratumCapacity*, *Pset_SolidStratumComposition*, *Pset_WaterStratumCommon*, *Pset_GeotechnicalStratumCommon*, and *Pset_GeotechnicalAssemblyCommon* are introduced for the aforementioned IFC types (buildingSMART, 2020b). However, there can be some shortcomings in these sets as they provide limited information compared to the amount of data that can be collected for geotechnical elements.

The literature holds many works on modelling underground layers and creating workflows and methodologies to better manage and use geotechnical data. However, many of these works do not address interoperability issues of the model and data as per the latest developments in open data formats or in a manner that takes into consideration the standardization of the process of preserving geotechnical data (Camila Andrea Sandoval Bustos, 2020; Kim and Gultekin-Bicer, 2018; Tegtmeier *et al.*, 2014; Yeniceli and Ozcelik, 2015; Zhang *et al.*, 2016; Zhang, Zhang, Tian, Liu, *et al.*, 2020; Zhang, Zhang, Tian, Li, *et al.*, 2020).

From another perspective, 3D modelling of underground structures in BIM models increases the quality of the analysis of underground conditions and highlights underlying issues in project locations where more investigative borehole drillings could be needed for example. Accordingly, modelling of underground geotechnical elements can be noted in major infrastructural projects around the world (MT Højgaard, 2016; RailBaltica, 2019). However, it is still a neglected aspect for most projects implementing BIM, where most do not model topographic, geological, and geotechnical conditions in their BIM model, and commonly stop at modelling foundation works (Berdiglyjov and Popa, 2019). This leaves a great amount of geotechnical data out of the BIM model to be present only in non-interoperable digital or even paper-based documents. Understanding and addressing knowledge gaps in geotechnical data in the early stages of a project can help reduce uncertainties and risks that can negatively affect project progress (Human and Jupp, 2016; Sibaii *et al.*, 2020).

Many vendors are developing software for modelling underground layers. An exploration was made on a number of these geotechnical engineering software involved in modelling underground elements based on data extracted from boreholes and geotechnical investigations. The exploration confirmed that there is a lack of a standardized methodology for handling geotechnical data, as well as shortcomings when it comes to preserving all data from geotechnical investigations in open data formats (Rincón, 2020; Sibaii, 2020; Tegtmeier *et al.*, 2009).

Furthermore, it is relevant to note that the parties involved in the making of the geotechnical report, like geologists and the institutes involved in doing the geotechnical investigation tests commonly do not have BIM modelling expertise. This diverts the task of integrating geotechnical data in the BIM model to the geotechnical engineers or the civil engineers involved in the design process of the structure, which most of the time does not happen and the traditional approach is followed. In this context, it can be understood that there is a need for a methodology that helps users, BIM experts or not, to get involved in the process of saving geotechnical data in a BIM format.

The present work aims at developing a BIM approach that would push for better use of geotechnical data from geotechnical investigations in a standardized BIM-based context. A workflow for dealing with geotechnical data is proposed, along with a general process map that explains how the workflow fits in the geotechnical data journey. The benefits of PDTs are harnessed through the creation of a standardized Borehole Data Template that would be used as a digital BIM readable format for geotechnical data extracted from geotechnical investigations. A script is developed using visual programming tools that would automate the process of modelling underground elements and saving geotechnical data in a BIM context, using only the data from the Borehole Data Template. Interoperability issues are addressed by exploring the use of IFC formats for model exporting. This process would make it an easier task for users of different backgrounds and different BIM proficiencies to get involved in the BIM approach while handling geotechnical data. To mimic a realistic design situation, a proprietary modelling platform was selected, Autodesk REVIT 2020, together with one of its scripting environments: Dynamo. The reason for this choice was related to the wide market representativity of this platform. However, the concepts underlying to the modelling and scripting are presented in a transversal manner, making them interconvertible to other platforms as much as possible.

The remainder of the paper is organized as follows. In section 2, the BIM-based workflow for handling geotechnical data is proposed. The methodology of creating the proposed Borehole Data Template is described in section 3. The method of using visual programming to model boreholes and underground layers and saving the data from the borehole PDT is discussed in section 4. The issues related to interoperability are discussed in section 5, along with an application to test the proposed workflow. Finally, conclusions are drawn in section 6.

2. WORKFLOW PROPOSAL FOR GEOTECHNICAL DATA MANAGEMENT

The workflow proposed for handling geotechnical data begins with the insertion of existing geotechnical data into the proposed Borehole Data Template (see Fig.1, tasks A & B). This step transforms the data from its non-BIM formats, whether paper or digital-based, into a standardized format, in the form of a spreadsheet (XLSX format or open formats such as ODS or FODS), that makes the data accessible for software and BIM platforms. The process of filling the information of a given borehole in the Borehole Data Template (henceforth mentioned as BDT) makes it become a Borehole Data Sheet (henceforth mentioned as BDS). In the next step, the scripting tool developed within this research is used to process the information of each relevant BDS (tasks C & D). Whenever the user wants to create an estimation solid model of the geotechnical layers covered by the domain of borehole data, a second part of the scripting tool is executed, and the necessary interpolation and geometry generation is made. This makes all the data available in the BIM model in a format that is adequate for IFC export, and both proprietary and non-proprietary formats of the model can be shared with other stakeholders (task E). It is further noted that the scripting tool developed is also capable of reconstituting BDS's from the borehole data available in the model, hence facilitating communication with stakeholders that may not be BIM-enabled.

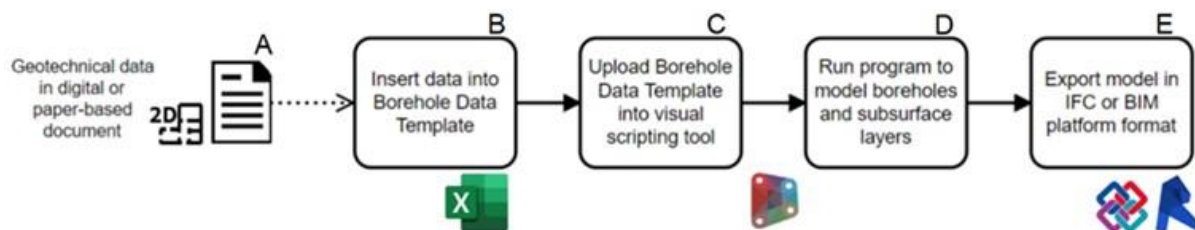


FIG. 1: Proposed workflow for transforming geotechnical data into BIM-based digital formats

If additional data exists from new borehole drillings or additional in-situ or laboratory tests, the user can simply update the model by repeating the process of the workflow. This reduces the repetition of processes that the traditional approach for handling geotechnical data suffers from. Other than the standardization and interoperability issues addressed, the workflow allows the data in a certain project to be always up to date and includes all efforts, past and present, of collecting geotechnical data. Moreover, the 3D modelling of boreholes and underground layers is made an easier process, so the benefits of BIM can be harnessed by all entities dealing with geotechnical data regardless of their BIM experience. It is also worth mentioning that having the ability to model underground elements in the BIM platform, reduces the need of users to purchase other software to model these elements, which reduces the costs for users and the need to know how to use other software. The two central enabling points for the proposed framework, which are addressed in the next sections, are: (i) the proposal of the BDT, addressed in section 3; (ii) the scripting tool developed for the creation of borehole objects and the resulting layers, as documented in section 4.

In the present section, some further elaboration is made regarding the inclusion of the tools developed herein in a wider perspective of a project workflow. The ISO 19650 series has been taken into account in the process of creating this workflow and the terminology used in the forthcoming reasoning and process map is based on this standard. It was assumed that the reader is proficient with such terminology, hence the necessary definitions were not provided. The workflow illustrated in the process map of Fig.2 focuses on the geotechnical data journey in a construction project. This specific illustrative project is based on a contractual relationship that is still widely used worldwide, that consists in the owner (appointing party) hiring an architect/coordinator (who takes the role of 'lead appointing party') to manage the design of a given building (Fig.2 A1). In such context, the lead appointing party shall be hiring several other appointing parties, namely for the elaboration of the structural/geotechnical design. In this workflow, the appointed party for structural/geotechnical design does not include the capacity to conduct in-situ testing, and if necessary, has to further hire another sub-appointed party: the geotechnical survey company.

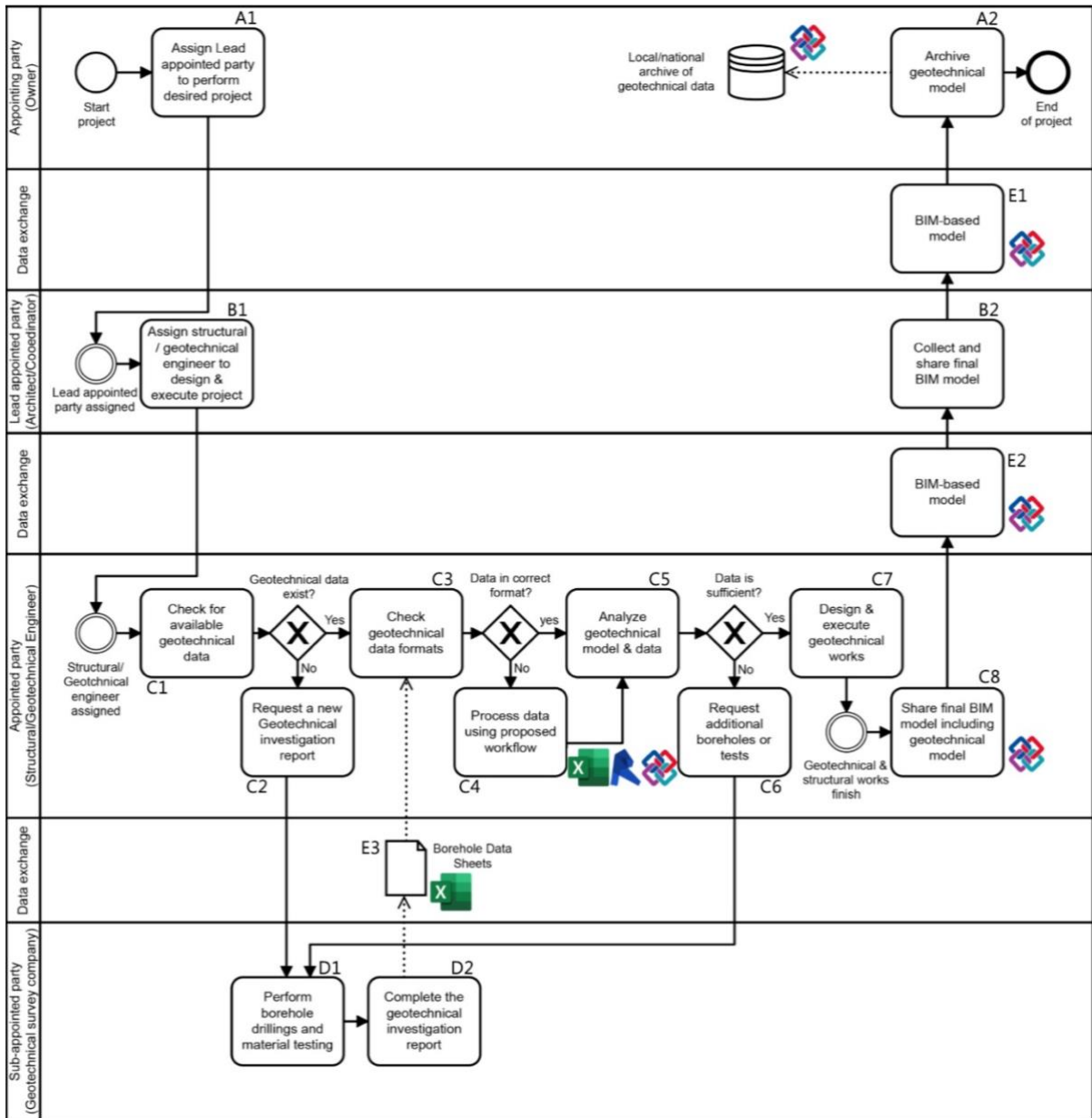


FIG. 2: A process map explaining the context where the proposed workflow would contribute to the geotechnical data journey

It is noted that other contractual relationships (e.g. Integrated Project Delivery) would bring the need for adaptations/variations to the process map. However, these would be minor within the scope of the information flow covered herein, in principle, hence the authors did not try to be exhaustive at this level.

The process shown in Fig.2 is now described in detail. It starts with the activity of hiring the lead appointed party on behalf of the appointing party (task A1). The lead appointed party in this context (an Architect, as mentioned before, who accumulates the coordination and architectural design tasks) hires the structural/geotechnical engineer, to perform the structural design, including the geotechnical aspects (task B1). The structural designer checks for available geotechnical data in the project, which could be in the form of paper or digital documents shared by the appointing party at the beginning of the project (task C1). If no geotechnical data exists, then there is a need to produce geotechnical data for the project, hence, the structural engineer requests a new geotechnical investigation report from the geotechnical survey company (task C2). Such sub-appointed party performs borehole drillings and the necessary material testing to produce the geotechnical investigation report (tasks D1 & D2). The data

commonly shared back at this point (E3) would normally be a paper-based or digital document with no specific standardized format. However, as per the proposed workflow, the expected deliverable is a set of Borehole Data Sheets, which includes in its parameters, as explained later on, a link to the original document of the geotechnical investigation report which preferably contains the produced BDS (data exchange E3).

After the data is received from the sub-appointed party or using previously existing data, the structural/geotechnical engineer would check if the data is in the correct format, as per the workflow of Fig.1 (task C3 in Fig. 2). If in any case, the data present is not in the formats expected as per the proposed workflow, the structural/geotechnical engineer is expected to process the data as per the proposed workflow to produce a geotechnical model that includes all geotechnical data (task C4). Once the BDS data is translated to the BIM platform in the correct format through the use of the scripting tools developed in this research (both the borehole objects and the interpolated layers, as shown in section 4), a well-informed decision would be made on whether the data is sufficient to finalize the geotechnical works. If any need arises for additional boreholes or material testing, the request is forwarded to the sub-appointed party, where the same process is followed and repeated as necessary until the data is sufficient (task C6).

Once the data is sufficient, the design and execution of geotechnical works are completed accordingly (task C7). When the geotechnical and structural works are finalized, the BIM model would be shared, in open data format, with the architect/coordinator (task C8, exchange E2), who would share this model along with any additional data from their part with the owner (task B2, exchange E1). These last exchanges E1/E2 might be processed differently and even directly in accordance with the selected CDE (Common Data Environment) solution/procedure, which is considered out of the scope of this description. At the end of the project, the geotechnical model would be archived privately, but also possibly in the local or national archive of geotechnical data, by the appointing party for use whenever needed in the future (task A2).

3. BOREHOLE DATA TEMPLATE (BDT)

The process of a geotechnical investigation results in a large number of parameters that are of great value for different stakeholders in a project. Different projects require different geotechnical data depending on the design requirements. The information requirements depend on the user's needs for modelling, design, and analysis. However, the process of extracting geotechnical data is mostly the same, through borehole drillings and material testing. The creation of a unified form for geotechnical data from borehole drillings falls within the standardization of processes in the information management context (particularly in BIM), of which the benefits have been mentioned earlier. In this context, a BDT is proposed that would include the relevant/necessary geotechnical data that can be extracted from boreholes and the material testing for use in all the lifecycle of a project by different stakeholders. This data template, being a digital BIM-friendly definition, would be easily associated with borehole objects created in the BIM platform hence complying with international object standards (NBS, 2019). The definitions made herein were set to be compatible with the existing definitions, regulations and recommendations (ISO 23386, 2020; ISO 23387, 2020; prEN 17473, n.d.).

3.1 Collection of parameters

To collect all the data necessary for the BDT, different sources were taken into account to understand which of the geotechnical parameters should be included in the template. Three sources were explored for that matter: (i) the geotechnical investigation report, (ii) parameters needed for the design of geotechnical works using manual calculations and geotechnical software, and (iii) tests related to underground water quality.

First Source:

The first and most influential source is the geotechnical investigation reports that are created after performing borehole drillings and laboratory and in-situ tests on materials extracted from the borehole. For this source, information was collected from geotechnical reports from different countries, mainly from the UK (RSK, 2018), Australia (NWC, 2012; TMR, 2019), and the USA (A3GEO, 2014). It is very important to note that the sources are based on existing regulations and recommendations for geotechnical report creation as seen in Table 1.

TABLE 1: Standards for geotechnical investigation and testing

Standard	Title
(ISO 14688-1, 2017)	Geotechnical investigation and testing - Identification and classification of soil
(ISO 14689, 2017)	Geotechnical investigation and testing - Identification and classification of rock
(ISO 17892-11, 2019)	Geotechnical investigation and testing - Laboratory testing of soil
(ISO 22475-1, 2006)	Geotechnical investigation and testing - Sampling methods and groundwater measurements
(ISO 22476-1, 2012)	Geotechnical investigation and testing — Field testing
(ISO 22282-1, 2012)	Geotechnical investigation and testing — Geohydraulic testing
(BS 5930, 2020)	Code of practice for ground investigation
(AS 1726, 2017)	Geotechnical Site Investigations
(ASTM-D2488-17e1, 2017)	Standard Practice for Description and Identification of Soils

The geotechnical investigation report produced for any project would contain general project data, borehole data, in-situ and laboratory test results, material descriptions, groundwater levels, among other data. The type of information can vary depending on the nature and purpose of the investigation. According to the analysis of reports and systematization made in the scope of this research, three groups of parameters could be singled (see Table 2). The first group of parameters holds general data that defines the project context and identity, the borehole's identity and conditions, and the material quantities used in the borehole. The second group of parameters is mainly about the identification and description of soils and rocks as per the standards of soil and rock identification and description. The third group is the laboratory and in-situ tests that are performed to gain accurate values of the parameters characterizing the underground layers. These values are significantly important for the design and analysis of geotechnical works.

Group one represents parameters that are typically sourced from the borehole site logs which contain data related to each borehole executed, and geotechnical reports performed that holds general project data. Accordingly Group one holds data about (i) geometrical data like coordinates, inclination, level, and depth, (ii) material quantities like drilling fluids used and their quantities, casing data, and core trays used, (iii) general data like names of the project, client, drilling company, and borehole name, start and finish dates of drilling, general project location and seismic zone of the area.

TABLE 2: Groups of parameters derived from geotechnical investigation reports

Group 1	Group 2	Group 3
Reference: RSK 2016; TMR 2016; NWC 2012; A3GEO, 2014	Reference: ISO 14688, ISO 14689, BS 5930, AS 1726, ASTM D2488 – 17e1	Reference: ISO 14688, ISO 22476, ISO 17892, ISO 22475, ISO 22477, ISO 22282
General information	Layers description	Laboratory and In-situ test results
ProjectName	Soil description	MoistureContent
ProjectLocation	SoilType	LiquidLimit
ProjectNumber	SecondaryConstituents	PlasticLimit
ClientName	Colour	BulkWeightDensity
SeismicZone	MoistureCondition	UnitWeightOfWetSoil
DrillingContractor	ConsistencyCohesive	UnitWeightOfDrySoil
JobNumber	ConsistencyNonCohesive	SpecificGravity
BoreholeName	GrainSizeAnalysis	MaximumDryDensity
TotalBoreholeDepth	Odour	OptimumMoistureContent
StartDate	Angularity	CohesionUndrained
FinishDate	PeatDescription	CohesionDrained
DrillRig	RelativeDensity	FrictionAngleUndrained
LoggedBy	Plasticity	FrictionAngleDrained
ReviewedBy	Grading	AngleOfDilation
BoreholeDiameter	Discontinuities	ModulusOfElasticityUndrained

GroundWaterDepth
BoreholeCoordinateSystem
BoreholeLocationLatitude
BoreholeLocationLongitude
BoreholeSurfaceLevel
CasingDiameter
CasingLength
LiningMaterial
LiningThickness
CapDepth
CapMaterial
DrillingFluid
FillingDepth
FillingMaterial
WaterLoadVolume
ConsumedDrillBits
BentoniteMudWeight
PolymerMudWeight
CoreTraysNumber
DrillingMethod
BoreholePlungeAngle
BoreholeAzimuthAngle
IsInclinometerInstalled
IsExtensometerInstalled
IsPiezometerInstalled

OrganicContent
SecondaryMinerals
BeddingDescription
AdditionalRemarks
Rock description
RockType
SecondaryConstituents
Colour
WeatheringCondition
StrengthCondition
DiscontinuityDescription
DiscontinuitySpacing
DiscontinuityAngleOfIncidence
DiscontinuityFrequency
Structure
Fabric
GrainSizeAnalysis
SecondaryMinerals
DestinctiveFeatures
TotalCoreRecovery
SolidCoreRecovery
RockQualityDesignation
AdditionalRemarks

ModulusOfElasticityDrained
CompressiveStrength
RockCompressibility
Shear Strength
TensileStrength
PoissonsRatio
CoefficientOfVolumeCompressibility
CoefficientOfConsolidation
PWaveVelocity
SwaveVelocity
Porosity
PHValue
ChlorideContent
SulphateContent
HorizontalPermeability
VerticalPermeability
PermeabilityBehaviour
HydraulicConductivity
GrainSizeAnalysis
SPTNValue
SPTCorrectedNValue
Resistivity
LoadBearingCapacity
ConePenetrationTest
PercolationTesting
MackintoshProbes
HandVane
PocketPenetrometer
CaliforniaBearingRatio
SchmidtHammer
AirVolume
BouldersVolume
ClayVolume
CobblesVolume
ContaminantVolume
FillVolume
GravelVolume
OrganicVolume
RockVolume
SandVolume
SiltVolume
WaterVolume

Data in group two is more specific to the underground layers, where parameters are defined as per the standard method of describing soil and rocks. The description of underground layers is typically made through a systemized way of description following a specific order. For example: Medium (particle size) soft (consistency) closely spaced (discontinuities) medium bedded (bedding) greyish brown (colour) slightly clayey (secondary constituent) SILT (soil type). The parameters chosen in group two represent each element of the description process for soil and rock.

In group three, parameters that result from various laboratory and in-situ tests were combined. Certain parameters can be calculated from different laboratory tests. For example, the friction angle of soil can be derived from more than one test, like Direct Shear Test, Tri-axial Shear Test, and Standard Penetration Tests. The Tri-axial shear test alone results in three parameters which are the friction angle, cohesion, and dilatancy angle, hence, these three parameters were added to the list. Following this reasoning, the rest of the parameters were collected based on the results of the tests conducted on material from borehole drillings. In-situ tests like Hand Vane and Pocket Penetrometer give results for the same parameters mentioned earlier like shear strength, and compressive strength, however, the test name was added as a parameter to separate it from the parameters calculated using laboratory tests.

Second source:

The second source of information was obtained from manual design processes for different types of foundation and other geotechnical works, and geotechnical design software that uses certain parameters for the design and analysis of geotechnical works. This source was considered since the data present in the BDT is to be used also in the context of structural/geotechnical design.

Manual design of some of the common geotechnical works was analyzed to understand the type of parameters used in the process of design. Mainly the design of piles, foundations, ground anchors, and slope stability was taken into account. The parameters collected from each are represented in Table 3. Noticeably some parameters have great importance as they can be found in almost all the design manuals explored like friction angle, cohesion, groundwater table, shear strength and unit weight.

TABLE 3: Common parameters needed for the manual design of geotechnical works

Geotechnical work		Piles	Slope stability	Foundations	Ground anchors
Reference		(Gedeon, 2014)	(Deng <i>et al.</i> , 2015)	(Handa <i>et al.</i> , 1984; Szygielski and Farrar, 2004)	(Weatherby, 1998)
Parameters needed for manual design and analysis	Friction angle	✓	✓	✓	✓
	Cohesion	✓	✓	✓	✓
	Unit weight	✓	✓	✓	✓
	SPT N value	✗	✗	✓	✓
	Young's modulus	✓	✗	✗	✗
	Bulk weight density	✗	✗	✓	✗
	Moisture content	✗	✗	✗	✓
	Groundwater table	✗	✓	✓	✓
	Shear strength	✓	✗	✓	✓
	Compressive Strength	✗	✗	✓	✓
	Consolidation	✗	✓	✗	✓
	PH & Chloride	✗	✗	✗	✓
Atterberg limits	✗	✗	✗	✓	

Then, a group of relevant software for geotechnical calculations was analyzed with basis on the respective user manuals. The needed input parameters were analyzed and put into comparison (see Table 4). It was noted that the

same parameters mentioned earlier as important, also appeared in this comparison with an additional two parameters which are Poisson's ratio and Young's modulus.

TABLE 4: Parameters needed for the design of geotechnical works in different geotechnical software

Software		(Plaxis 2D V20, n.d.)	(AllPile V7, n.d.)	(GEO5 V19, n.d.)	(Peysanj 5.2.2020.1107, n.d.)
Vendor		Benteley	CivilTech	Fine	NovoTech
Parameters needed for design and analysis	Friction angle	✓	✓	✓	✓
	Cohesion	✓	✓	✓	✓
	Unit weight	✓	✓	✓	✓
	SPT N value	✗	✓	✗	✗
	Young's modulus	✓	✓	✓	✓
	Poisson's ratio	✓	✓	✓	✓
	Angle of Dilation	✓	✗	✗	✗
	Groundwater table	✓	✓	✗	✓
	Shear strength	✓	✗	✗	✗
	Permeability	✓	✗	✗	✗
	Consolidation	✗	✗	✗	✓

The list of parameters collected from geotechnical reports was comprehensive enough to contain all the parameters mentioned in the manual design processes as well as the parameters needed for design and analysis in geotechnical software. However, it was an important step to verify there was no lack of important parameters in the list of parameters collected from geotechnical reports, as well as to highlight the importance of some parameters.

Third source:

Water can be encountered during the drilling of boreholes, hence, it was important to explore the parameters relevant to testing water quality, as the purpose of the drilling could be related to the use or monitoring of underground water. Accordingly, the relevant parameters that classify the water constituents to understand if it is potable were considered, along with other parameters related to the monitoring of underground water (NDSU, 2019; USGS, 2010) (see Table 5). Additional to water layers, voids can be encountered in the process of borehole drilling, however, no parameters are commonly collected other than the location of the void in a borehole. Accordingly, no parameter sets are proposed in that context.

TABLE 5: Parameters for water layers in boreholes

Parameters for water in boreholes			
Colour	Hardness	DissolvedOxygen	Beryllium
Odour	Arsenic	Calcium	Boron
WaterPH	Selenium	Magnesium	Cadmium
ColiformBacteria	Uranium	Potassium	Chromium
Nitrates	PesticideContamination	Carbonate	Cobalt
Manganese	MethyleneBlueActiveSubstances	Bicarbonate	Copper
Alkalinity	Strontium	Lead	Lithium
Sodium	Methane	Silica	Molybdenum
WaterChloride	Radium	Ammonia	Nickel
Fluoride	BTEX	Orthophosphate	Strontium
WaterSulphate	Bromide	Phosphorus	Thallium
Iron	Barium	TotalOrganicCarbon	AnnualRange
TotalSuspendedSolids	Temperature	DissolvedOrganicCarbon	AnnualTrend
TotalDissolvedSolids	Conductivity	Antimony	-
WaterFlow	IsFreshWater	Vanadium	-

3.2 Borehole Data Template proposal

The nomenclature of the collected parameters from the three sources was compared with the existing property sets introduced in the latest version of the IFC schema, IFC4.3 RC2, which are related to underground elements to ensure that interoperability conditions are satisfied as explained further in section 5. The following main property sets were considered: Pset_solidStratumCapacity, Pset_SolidStratumComposition, Pset_BoreholeCommon, and Pset_WaterStratumCommon (buildingSMART, 2020b). Table 6 shows the parameters collected from Pset_SolidStratumCapacity and Pset_SolidStratumComposition property sets which hold parameters related to underground soil and rock layers, Pset_BoreholeCommon that contains parameters related to the borehole's general information, and Pset_WaterStratumCommon which contains some parameters related to water in boreholes.

TABLE 6: IFC parameters for underground elements

Pset_SolidStratum Capacity	Pset_SolidStratum Composition	Pset_BoreholeCommon	Pset_WaterStratum Common
CohesionBehaviour	AirVolume	BoreholeState	AnnualRange
FrictionAngle	BouldersVolume	CapDepth	TidalRange
FrictionBehaviour	ClayVolume	CapMaterial	IsFreshWater
GrainSize	CobblesVolume	FillingDepth	SeicheRange
HydraulicConductivity	ContaminantVolume	FillingMaterial	TidalRange
LoadbearingCapacity	FillVolume	GroundwaterDepth	WaveRange
NValue	GravelVolume	LiningMaterial	-
PermeabilityBehaviour	OrganicVolume	LiningThickness	-
PoisonsRatio	RockVolume	-	-
PwaveVelocity	SandVolume	-	-
Resistivity	SiltVolume	-	-
SettlementBehaviour	WaterVolume	-	-
SwaveVelocity	-	-	-

It was confirmed that most of the parameters in the IFC property sets Pset_SolidStratumCapacity, Pset_SolidStratumComposition, Pset_WaterStratumCommon and Pset_BoreholeCommon were present within the parameters from the aforementioned sources under the same name. However, some parameters have different nomenclatures, as compared to the ones from previous sources. For example, FrictionAngle in IFC is introduced in two parameters named '*FrictionAngleDrained*' and '*FrictionAngleUndrained*' in Table 2, group 3. The issue of naming for parameters with different names will be addressed later on in section 5, where it will be discussed how parameters can be exported in names that match IFC property sets since they are particularly important for the interoperability of borehole objects. Additionally, concerning the parameters of the property set Pset_SolidStratumComposition in Table 6, the IFC suggests a volumetric measurement, however, since these values can be presented in percentile or volumetric measurements a note is added in the 'Note' column mentioning that the user can insert the values in percentile or volumetric measurements and asks that the unit be included within the value itself. These parameters express the material composition of a stratum which is used for the classification of soil based on ISO 14688 (buildingSMART, 2020c; ISO 14688-1, 2017; Kovačević *et al.*, 2018).

A PDT is divided into different categories, with different parameters within each that should be filled with certain values. The layout of the template proposed herein is based on CIBSE master PDT (CIBSE, 2021), despite the fact that such master template includes categories and parameters that do not fit with the Borehole Data Template (electrical data, performance data, sustainability data, etc.). Hence the Borehole Data Template was adapted for the specific parameters it should include and exclude. Accordingly, the parameters collected from the previous section were segregated into five categories, as visible in the proposed BDT, schematically shown in Table 7: (i) general information, (ii) soil layer data, (iii) rock layer data, (iv) water layer data, and (v) void layer data.

Each category in the template has 4 columns: parameters, values, units, and notes that are added to help the user fill the parameters. The '*value*' is the only column that is filled by the user. The structure and columns are shown for the "General Information" category of the BDT in Table 8, however the full BDT can be found in Table 1 in

Appendix A of this document. An additional column is added with the numbering of the rows of the full BDT (Table 1 in Appendix A) on its left-hand side, to facilitate the reference to a given location of the template throughout the upcoming paragraphs. The BDT is provided in XLSX format in the supplemental material of this paper.

TABLE 7: Schematic representation of the BDT for a borehole with layers: Soil, Void, Water, and Rock consecutively

Template name	Borehole Data Template		
Template category	Geotechnical data		
Suitability for use	Geotechnical engineering - BIM		
Parameter Name	Value	Units	Notes
General Information			
-	-	-	-
Borehole Layer Distribution			
Soil layer data			
Soil layer description			
-	-	-	-
Laboratory Test Results			
-	-	-	-
In-Situ Test Results			
-	-	-	-
Void layer data			
-	-	-	-
Water layer data			
-	-	-	-
Rock layer data			
Rock layer description			
-	-	-	-
Laboratory Test Results			
-	-	-	-
In-Situ Test Results			
-	-	-	-

The schematic representation of the structure of the BDT in Table 7 is done to assist in explaining the global structure of the template and the operating principles to be done when multiple layers of soil/rock occur (i.e. the usual situation in most boreholes). The example shown in Table 7 corresponds to a case with four layers, in which the shallow layer is a soil layer, the second and third layers are respectively void and water layers and the deepest one is a rock layer. This particular BDT becomes organized in a total of 5 sections, with the first section, the general information part, is common for all the BDT parts. The remaining 4 sections correspond to the actually encountered layers: layer 1: Soil; layer 2: Void; layer 3: Water; and layer 4: Rock. It is therefore an adaptive data template, which expands and contracts in a predictable manner according to the number of layers encountered.

The authors were careful to name the parameters following the BIM object standards (NBS, 2019; OBOS, 2018), as these names would be assigned to the borehole object in the BIM platform. Hence, the PascalCase convention was used to write the parameters, and the international system of units was adopted for the values. The value 'n/a' should be used in the case of no value present, and Boolean variables, 'True' or 'False', are identified using the interrogative format (e.g. *IsInclinometerInstalled*, as shown in row 43 of Table 1 in Appendix A).

Also, there are some parameters, such as all of those in the group 'Laboratory Test Results' in the 'Soil Layer Data' part (Table 1 in Appendix A, row 71) in which several results may exist at several depths (or even more than one may exist at a given depth) in a manner that is not necessarily related to the number of layers encountered. For that reason, the data template puts this information in a vector format, to accommodate an open number of

multiple instances of results. For example, in row 72 of the BDT, the ‘*MoistureContent*’ could be filled with [4,40];[12,80], in correspondence to two tests carried at depth 4m with a result of 40% and at 12m with a result of 80%.

Table 8: General Information category in the Borehole Data Template

Template name	Borehole Data Template		
Template category	Geotechnical data		
Suitability for use	Geotechnical engineering - BIM		
Parameter Name	Value	Units	Notes
General Information			
BhProjectName		Alphanumeric	
BhProjectLocation		Alphanumeric	
BhProjectNumber		Alphanumeric	
BhClientName		Alphanumeric	
SeismicZone		Alphanumeric	Zone (1, 2A, 2B, 3, 4)
BhDrillingContractor		Alphanumeric	
BhJobNumber		Alphanumeric	
BoreholeName		Alphanumeric	
BhClassificationSystem		Alphanumeric	
BhClassificationCode		Alphanumeric	
TotalBoreholeDepth		Number	
BhStartDate		Alphanumeric	
BhFinishDate		Alphanumeric	
DrillRig		Alphanumeric	
BhLoggedBy		Alphanumeric	
BhReviewedBy		Alphanumeric	
BoreholeState		Alphanumeric	The state the borehole or trial pit has been left in
BoreholeDiameter		mm	
GroundWaterDepth		m	From borehole surface
BoreholeCoordinateSystem		Text	(mandatory field)
BoreholeLatitude		Alphanumeric	(mandatory field)
BoreholeLongitude		Alphanumeric	(mandatory field)
BoreholeSurfaceLevel		Number	From sea level (mandatory field)
GroundwaterDepth		m	Depth measured from borehole surface level
CasingDiameter		mm	
CasingLength		m	
LiningMaterial		Alphanumeric	
LiningThickness		mm	
FillingDepth		m	
FillingMaterial		Alphanumeric	
DrillingFluid		Text	
WaterLoadVolume		Litre	
ConsumedDrillBits		Number	
BentoniteMudWeight		Kg	
PolymerMudWeight		Litre	
CoreTraysNumber		Number	
DrillingMethod		Alphanumeric	
BoreholePlungeAngle		Degrees	
BoreholeAzimuthAngle		Degrees	
CapDepth		m	
CapMaterial		Alphanumeric	
IsInclinometerInstalled		True/False	
IsExtensometerInstalled		True/False	
IsPiezometerInstalled		True/False	
GeotechnicalReportURL		Alphanumeric	

Moreover, to avoid potential conflicts of parameter naming with other parameters that might previously exist in other contexts in the BIM models, the prefix ‘Bh’ has been added in some parameter names. Examples of parameters in such conditions were ‘*ProjectName*’ or ‘*ProjectLocation*’, which became ‘*BhProjectName*’ or ‘*BhProjectLocation*’. It is important to note that many parameters that belong to the ‘*Soil Layer Data*’ also exist

in the *'Rock Layer Data'*. Accordingly, the addition of the word 'Rock' to the duplicated parameters was made to avoid conflict in parameter names within the BDT, and especially in the process of data transfer from the BDT to the BIM platform. Example of such parameters is *'ShearStrength'* and *'PoissonsRatio'*, which became *'RockShearStrength'* and *'RockPoissonsRatio'* (Table 1 in Appendix A, rows 179 & 181). The same reasoning was followed through the rest of the template on parameters with similar names. The five categories included a total number of 253 parameters.

The BDT is to be used in the context of modelling underground elements, mainly boreholes and subsurface layers. Accordingly, a note stating 'Mandatory field' was added in the *'Note'* section of parameters related to coordinates and level (Table 1 in Appendix A, row 21 to 24) so that the modelling of geotechnical elements is possible, and on the basic layer data like *'SoilType'* and *'RockType'* (Table 1 in Appendix A, row 53 & 130) so that a minimum of data to classify the objects modelled is available.

Moreover, it is noteworthy to discuss the conditions around two proposed parameters. First, the *'GeotechnicalReportURL'* parameter (Table 1 in Appendix A, row 46), where it is supposed to contain a link to the original document of the geotechnical report. Depending on the project contractual agreement the document would be made available for the client, taking into account the necessary precautions concerning the privacy of information by implementing special authentication procedures for data access. The contract would also state the conditions of maintaining the document available online permanently.

Second, the *'LayerIdentifier'* parameter for soil, rock, water, and void layers (Table 1 in Appendix A, rows 50, 129, 194, & 257), where the user is instructed to input a unique identifier for each layer. This parameter is important to ensure the uniqueness of each layer in the BDT when translated to a BIM object, specifically when multiple layers exist with similar parameters in a borehole or even in the project. Accordingly, it was suggested that it would be inserted based on the following form: Borehole name - "S, R, W, or V" for Soil, Rock, Water, or Void layer - Layer number in a borehole - Latitude - Longitude - Level, noting that all values are to be introduced as absolute values and decimal points to be omitted while keeping the decimal numbers. For example: BH1-S-2-33889641-35470461-6052 is for a borehole layer with Borehole name: BH1, layer type: Soil, layer number: 2, latitude: 33.889641, longitude: -35.470461, and borehole level: 60.52.

From a practical point of view, and taking advantage of the BDT structure, the entire set of results of a geotechnical inspection (i.e. several boreholes) could be introduced into a single spreadsheet file with several tabs. Accordingly, each Borehole Data Sheet would be on a single tab of the spreadsheet.

4. MODELLING BOREHOLES AND SUBSURFACE LAYERS

The borehole object structure is an adaptive one, where each borehole has a different layers configuration. With that in mind, the first stage of this process was the creation of classes of objects representing the different layers in boreholes that will be used as a structure for the main borehole assembly. The borehole assembly is created by arranging the mentioned classes as per the unique distribution of layers of each borehole. Accordingly, four different classes of objects were created, as Revit families using adaptive components, to represent soil, rock, water, and void layers in a borehole. Each element of the borehole has a set of parameters based on the proposed parameters in the BDT, as seen in Table 9. This proposed structure for the borehole object creation will be the base for a smooth transfer of the model to the IFC format, as shown in Table 10 in section 5.

TABLE 9: Borehole elements parameters from BDT

Element	Parameters from BDT (Table 1 in Appendix A)
Borehole assembly	<i>'General Information'</i> (rows 2 to 46)
Soil class	<i>'Soil Layer Data'</i> (rows 48 to 126)
Rock class	<i>'Rock Layer Data'</i> (rows 127 to 192)
Water class	<i>'Water Layer Data'</i> (rows 193 to 255)
Void class	<i>'Void Layer Data'</i> (rows 256 to 259)

Currently, there is no specific Revit category for boreholes (a category in this platform is ‘Columns’, and an example of a family of that category is ‘Circular Hollow Section - Column’), hence all the geotechnical objects were created under the category “Generic models”, which is used for elements outside the Revit library of categories. The subsurface layers were created under the Revit category “Site”, which is the most relevant type for subsurface layers currently present in Revit. BIM object standards were kept in mind during the process of creating the borehole elements (NBS, 2019; OBOS, 2018). The names of the parameters in the classes of objects and the borehole assembly were written in the same way as the parameters in the BDT to ensure that the data correlated with each parameter is easily accessed when using the visual programming tool.

A visual programming script was created with the following objectives: (i) to model borehole elements and populate their parameters with information from the BDS; (ii) to use the borehole information to produce the necessary underground solid layers in the modelling platform. The script of the first and second objectives is further explained in modules 1 and 2 respectively. In this work, the selected BIM platform was Autodesk Revit 2021.1.2, which inherently operates with the visual programming tool Dynamo 2.6.1.

Module 1:

In regards to module 1 of the visual programming script, an algorithm in Dynamo was created to model the boreholes as per the borehole structure explained above (see Fig. 3). First, the BDS XLSX file is used as input for the script by linking the excel file of the boreholes to the script, and all the data is extracted into the scripting program for segregation (tasks a & b). Next, the geometrical data from the BDS, mainly coordinates and levels, are extracted and used to geometrically represent the boreholes (tasks e & g). In this step, the algorithm models the boreholes by assembling the classes of objects mentioned earlier to create all the boreholes in the project. Meanwhile, the script extracts the relevant parameters data from the BDS and use them to populate the parameters in the created borehole elements as per the distribution of parameters in the borehole assembly and classes of objects within (tasks c, d, & f). The output of this module is the borehole objects with populated parameters as per the attached BDS in the BIM platform (task g).

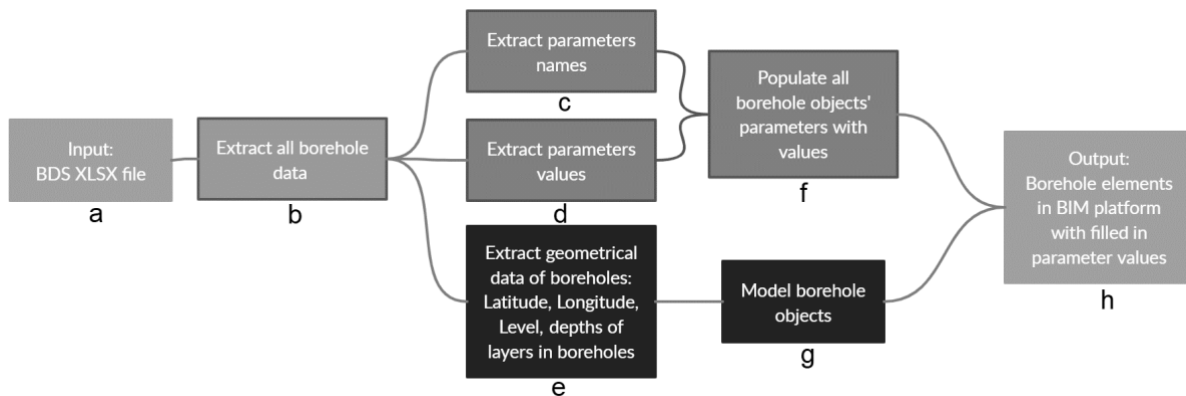


FIG. 3: Workflow of module 1

If the user wishes to update the model in the case of additional boreholes being introduced, the user needs only to update the BDS in the XLSX file and link it again to the module 1 script and run it to update the model in the BIM platform.

Module 2:

In module 2 of the visual programming script, it is intended to model subsurface layers based on the borehole data (see Fig. 4). First, the data extracted in module 1 is organized based on subsurface layers, instead of boreholes (tasks a & b). Then the geometrical data is extracted from the BDS for each layer separately (task c). For example, the coordinate data of all the boreholes of the first layer are segregated to be used to model the first layer. Accordingly, the top and bottom surfaces of each layer were modelled using the concept of triangulation between points which is available in predefined commands in the scripting tool (task e). Then the surfaces were used to create a solid mass representing each layer through the “loft” command. After the solid masses are created the parameter ‘LayerType’ is added to these layers (task f).

The parameter ‘*LayerType*’ contains the values of the parameters ‘*SoilType*’, ‘*RockType*’ or “*Water*”, or “*Void*”. These values are extracted from the BDS and populated in the subsurface layers created (tasks d & g). The reasoning behind including only this parameter in the subsurface layers is that the stakeholders involved in the design and analysis process of geotechnical data rely on accurate borehole data, and are more likely to rely on data from nearby boreholes for a certain foundation, for example. To include parameters for the subsurface layer that would show, for example, the average of the values of a certain parameter from the surrounding boreholes would mean showing inaccurate data. This is relevant because the same layer can have different characteristics like weathering and structure conditions from one borehole to the other. It is important to note that the complicated nature of the underground might introduce underground conditions that the script might not be able to detect and hence require human intervention to allow a more accurate model to be produced.

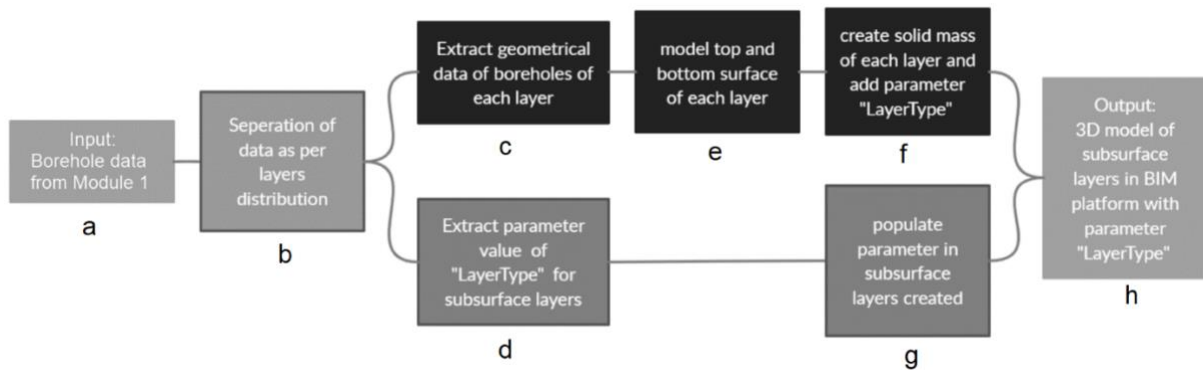


FIG. 4: Workflow of module 2

5. INTEROPERABILITY AND APPLICATION

Interoperability

Interoperability is an important aspect to consider when working with software in a BIM context to allow an easy and fast exchange of information between the BIM platform and any other software used by any stakeholder involved, whether for analysis, design or any other purpose. In the case of the present work, it is relevant to address the interoperability of the created model so that it is exported into a format independent of the software used to create it. Two aspects were taken into consideration in the process of exporting the model, the geometrical and non-geometrical information aspects.

The current IFC version IFC4.3 RC2 introduces two entity types for geotechnical elements under the type *IfcGeotechnicalElement*. One is the *IfcGeotechnicalAssembly* which in turn branches out to three IFC entity types, *IfcBorehole*, *IfcGeomodel*, and *IfcGeoslice*. The second main type *IfcGeotechnicalStratum* includes *IfcSolidStratum*, *IfcVoidStratum*, and *IfcWaterStratum*, these three types would be included under the three assemblies under *IfcGeotechnicalAssembly* (see Fig. 5).

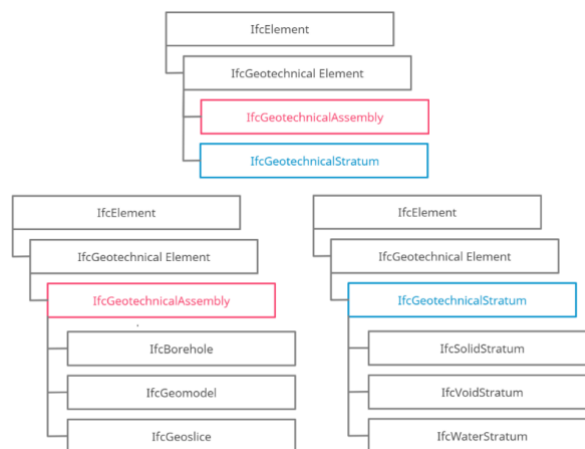


FIG. 5: IFC inheritance diagrams for geotechnical elements adapted from (buildingSMART, 2020b)

The model is expected to be exported, as per the mentioned IFC version. However, since the current version of the BIM platform used is not adapted to the latest updates in IFC, another framework must be adapted for the export of the created geotechnical elements. Later on when the BIM platform can export as per the current IFC developments, then the export would be made as per the workflow that conforms to the latest IFC developments. Accordingly, the export frameworks are discussed below.

For BIM platforms that conform with IFC4.3 RC2, the classes that constitute the borehole, which are soil, rock, water, and void Revit families, would export as the IFC types, *IfcSolidStratum*, *IfcVoidStratum*, and *IfcWaterStratum*. The borehole assembly would be exported as *IfcBorehole*. The subsurface layers would follow the same structure but would be exported as *IfcGeomodel* (see Table 10). The entity types under *IfcGeotechnicalStratum* can be separately identified in the IFC file based on their inheritance whether from *IfcBorehole*, or *IfcGeomodel*.

For BIM platforms that do not yet conform with IFC4.3 RC2 version, as the state of the BIM platform used for this work. All borehole elements are exported as “*IfcBuildingElementProxy*”, which is used for element types not included in the IFC type’s library within the BIM platform. Whereas, the subsurface layers are exported as “*IfcSite*”, which conforms to the chosen category chosen in the current BIM platform for subsurface layers.

TABLE 10: Revit objects and their perspective IFC types

Revit object	IFC type
Borehole Soil Layer	<i>IfcSolidStratum</i>
Borehole Rock Layer	<i>IfcSolidStratum</i>
Borehole Water Layer	<i>IfcWaterStratum</i>
Borehole Void Layer	<i>IfcVoidStratum</i>
Borehole assembly	<i>IfcBorehole</i>
Subsurface layers	<i>IfcGeomodel</i>

In regards to the export of parameters, it was important to take into account the property sets proposed by IFC for geotechnical elements mentioned earlier in section 3. The current IFC property sets do not include all the proposed parameters in the BDT, however, future developments of the IFC property sets might consider the proposed parameters to be included in them. With that in mind, the process of exporting all the parameters present in the created boreholes is discussed.

First, from the BIM platform aspect, if the platform used is updated to export properties as per the IFC version IFC4.3 RC2, then the user would choose the command “export IFC property sets” to automatically export all the parameters in the geotechnical elements modelled that have similar names as the ones in the IFC property sets. The rest of the parameters would be exported using the option “Export user-defined property sets”, which allows the parameters to be exported under custom-named categories and custom parameter names. However, the current BIM platform used does not support the proposed property sets in the aforementioned IFC version.

Accordingly, all the parameters were exported using the option “Export user-defined property sets”. The parameters of the main borehole objects were exported under a category name *Pset_BorholeData*, and the soil, rock, water and void layer’s properties present in their corresponding object classes were exported under the category names *Pset_SoilData*, *Pset_RockData*, *Pset_WaterData*, and *Pset_VoidData*. The parameter of the subsurface layer was exported under the category name *Pset_SubsurfaceLayerData*.

Future developments of the BIM platform might allow for the export of parameters directly using the predefined IFC property sets. However, parameters must be exported from the BIM platform to IFC using the same names defined in the IFC property sets to ensure no data loss in the process. With that in mind, it was important to attend to the issue that some parameters have different names in the BDT than the ones in IFC. For example, parameters that included a prefix ‘Bh’ or ‘Rock’ like ‘*BhGroundWaterDepth*’ or ‘*RockPoissonsRatio*’ need to be exported with the same name as the ones in the IFC property sets which are ‘*GroundWaterDepth*’ and ‘*PoissonsRatio*’. The solution of this issue is simple as the BIM platform, Revit in this case, allows the user to export parameters as per custom parameter names to IFC using the same command mentioned earlier ‘Export user-defined property sets’.

The model was exported in the IFC format using the IFC4 design transfer view export scheme that allows the user to modify elements and spaces in the received model. This ensures that the model can be used in the future for tasks that require model editings such as excavation visualization and quantity takeoffs.

Application

To put the proposed workflow to the test, real data from a project was used. The project location and name were undisclosed. The project included 4 boreholes performed in 2005 and 4 others in 2012. The BDSs were prepared for the boreholes by populating the relevant properties with data collected from the available geotechnical investigation reports. As the investigation reports used herein were one of important sources for the creation of the proposed BDT, the BDT was able to hold all the information provided in the geotechnical investigation reports. The 200 pages of the geotechnical reports were transferred to around 75 pages of BDSs containing around 2000 parameters in a file that is not larger than 150 KiloBytes (KB), which later became an IFC file of no more than 400 KB.

Next, modules 1 and 2 were implemented to create the borehole elements and the subsurface layers in the BIM platform, as well as populate the parameters with values (see Fig. 6a & b). Then the model was exported as per the discussion above to IFC as seen in Fig. 7. Next, to demonstrate how the model can be updated when additional boreholes are introduced, the same procedure was performed on the boreholes from 2005 and the BIM model was updated (see Fig. 6c & d). It can be noted how the combined model gives a more accurate overview of the underground conditions in the project. It can be seen how an additional layer of concrete, highlighted in grey, appears in the model after the boreholes from 2005 were introduced. As the amount of data in the model increases, the uncertainties of underground conditions decrease.

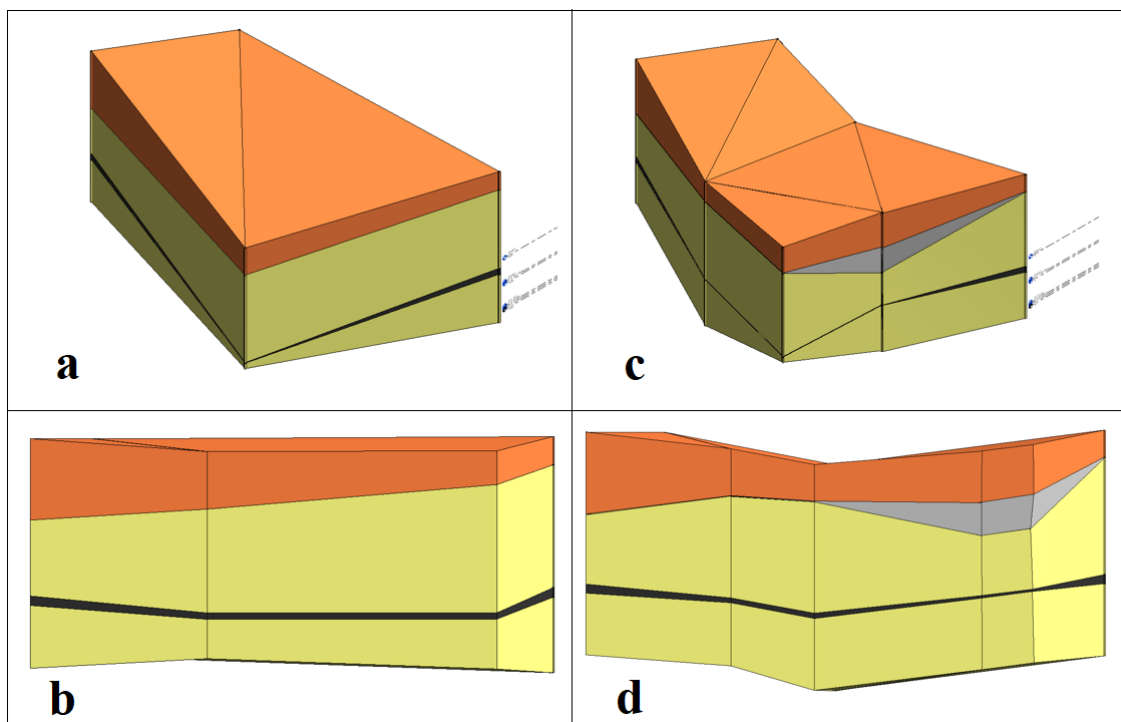


FIG. 6: Model of boreholes and subsurface layers in the BIM platform from the 2012 investigation (a & b), and from the 2005 and 2012 investigations combined (c & d)

The final IFC model consisted of 5 underground layers, 32 borehole elements, and 1895 parameters. Its thorough inspection allowed to validate that its graphical and non-graphical data, as set in the proprietary model of Revit, had been exported without any losses. Such inspection of the file for validation included several aspects. Regarding the graphical data, first the coordinates, extruded solids, and general shape of randomly selected boreholes were selected in the IFC model, and they were compared with their counterparts in the Revit model. Then, the shapes and coordinates of the 4 created subsurface layers in the IFC model were compared with the Revit model. The results of comparing graphical data were positive in all aspects, indicating a successful export of the proprietary

model to IFC. To validate that non-graphical data was fully translated from Revit to the IFC model, schedules were created for the properties and values inside all borehole elements in Revit and the IFC model. The results were thoroughly compared to check if any loss of data occurred. The results of these checks were 100% positive. This process of validation was made manually in this work, but it is important to note that validation checks can be automated as well by creating scripts that check for existing properties in exported geotechnical elements, like boreholes, based on the properties in the proposed BDT.

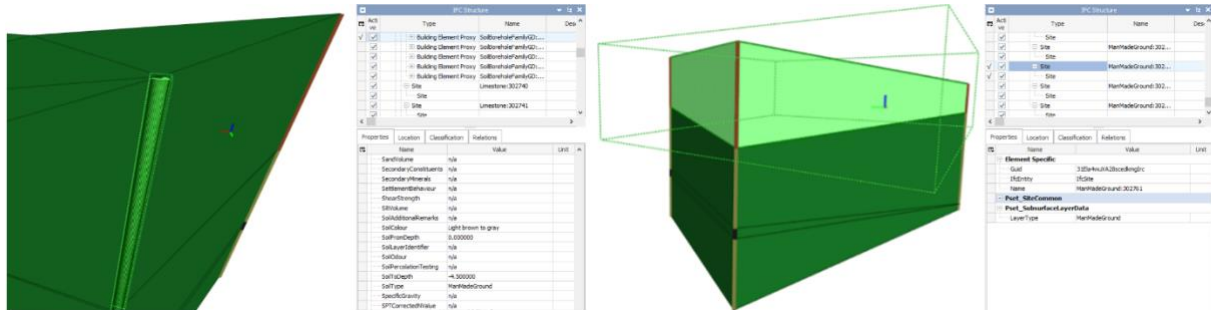


FIG. 7: IFC model showing borehole and properties (left) and subsurface layers and properties (right)

6. CONCLUSION

This study presented a workflow for handling geotechnical data that takes into consideration the standardization of processes by harnessing the benefits of PDTs, and the Interoperability of the data by the use of IFC. A process map was presented to indicate how the presented workflow would fit in the geotechnical journey in the context of a common contractual relationship where geotechnical data is handled. It showed how the proposed workflow can help in reducing the processing time of geotechnical data between stakeholders, by harnessing the benefits of the BIM approach. It also highlighted how the process would end with a richer archive that holds data in open data formats.

A Borehole Data Template is proposed to transform geotechnical data into a BIM readable format. The data present in it was confirmed to be enough to be used in different software for geotechnical modelling and analysis. However, visual programming tools were used to create a program that, using the data from the proposed Borehole Data Template, makes the process of modelling boreholes and underground layers an automated process for users dealing with geotechnical data. The program creates the model directly in the BIM platform, which reduces the need for users to own different software for modelling geotechnical elements and be able to visualize and analyze the geotechnical data at hand. This encourages users of BIM to incorporate geotechnical data in their BIM model of the asset, which in turn would yield many benefits on their projects. The created model and geotechnical parameters were successfully exported to the IFC format to ensure model interoperability. An application was conducted to put the workflow to the test and demonstrate the geotechnical model created in the BIM platform and its successful export to IFC format. This work is a step toward better use of geotechnical data in the construction industry.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX A: BOREHOLE DATA TEMPLATE PROPOSED

Table 1: Borehole Data Template

	Template name	Borehole Data Template		
	Template category	Geotechnical data		
	Suitability for use	Geotechnical engineering - BIM		
	Parameter Name	Value	Units	Notes
1	General Information			
2	BhProjectName		Alphanumeric	
3	BhProjectLocation		Alphanumeric	
4	BhProjectNumber		Alphanumeric	
5	BhClientName		Alphanumeric	
6	SeismicZone		Alphanumeric	Zone (1, 2A, 2B, 3, 4)
7	BhDrillingContractor		Alphanumeric	
8	BhJobNumber		Alphanumeric	
9	BoreholeName		Alphanumeric	
10	BhClassificationSystem		Alphanumeric	
11	BhClassificationCode		Alphanumeric	
12	TotalBoreholeDepth		Number	
13	BhStartDate		Alphanumeric	
14	BhFinishDate		Alphanumeric	
15	DrillRig		Alphanumeric	
16	BhLoggedBy		Alphanumeric	
17	BhReviewedBy		Alphanumeric	
18	BoreholeState		Alphanumeric	The state the borehole or trial pit has been left in
19	BoreholeDiameter		mm	
20	GroundWaterDepth		m	From borehole surface
21	BoreholeCoordinateSystem		Text	(mandatory field)
22	BoreholeLatitude		Alphanumeric	(mandatory field)
23	BoreholeLongitude		Alphanumeric	(mandatory field)
24	BoreholeSurfaceLevel		Number	From sea level (mandatory field)
25	GroundwaterDepth		m	Depth measured from borehole surface level
26	CasingDiameter		mm	
27	CasingLength		m	
28	LiningMaterial		Alphanumeric	

29	LiningThickness	mm	
30	FillingDepth	m	
31	FillingMaterial	Alphanumeric	
32	DrillingFluid	Text	
33	WaterLoadVolume	Litre	
34	ConsumedDrillBits	Number	
35	BentoniteMudWeight	Kg	
36	PolymerMudWeight	Litre	
37	CoreTraysNumber	Number	
38	DrillingMethod	Alphanumeric	
39	BoreholePlungeAngle	Degrees	
40	BoreholeAzimuthAngle	Degrees	
41	CapDepth	m	
42	CapMaterial	Alphanumeric	
43	IsInclinometerInstalled	True/False	
44	IsExtensometerInstalled	True/False	
45	IsPiezometerInstalled	True/False	
46	GeotechnicalReportURL	Alphanumeric	
47	Borehole Layer Distribution		
48	Soil layer data		
49	Soil layer description		
50	SoilLayerIdentifier	Alphanumeric	BoreholeName-S-layer number-latitude-longitude-level (absolute values, keep decimals, omit decimal points) e.g. BH1-S-1-33889641-35470461-6052 (mandatory field)
51	SoilFromDepth	m	(mandatory field)
52	SoilToDepth	m	(mandatory field)
53	SoilType	Text	SAND, SILT ... (mandatory field)
54	SecondaryConstituents	Text	Clayey, Silty, gravely... (add tertiary constituents if present)
55	SoilColour	Text	(Lightness, Chroma, Hue): Light Reddish Brown
56	MoistureCondition	Text	Dry, moist, or wet
57	ConsistencyCohesive	Text	Very soft, soft, firm, stiff, very stiff, hard
58	GrainSize	Alphanumeric	mm or boulders to clay definitions

59	ConsistencyNonCohesive	Text	Very loose, loose, medium dense, dense, very dense
60	SoilOdour	Text	Camphor, Musk, Floral, Vinegar ...
61	Angularity	Text	For course soil: Angular, Subrounded, Rounded ...
62	PeatDescription	Text	For organic soil: condition, constituents, decomposition ...
63	RelativeDensity	%	Density index
64	Plasticity	Text	Low plasticity, intermediate plasticity, high plasticity ...
65	Grading	Text	Well graded, poorly graded ...
66	Discontinuities	Text	Wide, medium, close; fissures, shears ...
67	OrganicContent	Text	Slightly organic, organic, very organic
68	SecondaryMinerals	Text	Shelly, calcareous ...
69	BeddingDescription	Text	Very thickly, thickly, medium, thinly ...
70	SoilAdditionalRemarks	Alphanumeric	Zoning, defects, cementation
71	Laboratory Test Results		
72	MoistureContent	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
73	LiquidLimit	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
74	PlasticLimit	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
75	BulkWeightDensity	Alphanumeric	[Sample depth, result in KN/m ³]; [Sample depth, result in KN/m ³]
76	UnitWeightOfWetSoil	Alphanumeric	[Sample depth, result in KN/m ³]; [Sample depth, result in KN/m ³]
77	UnitWeightOfDrySoil	Alphanumeric	[Sample depth, result in KN/m ³]; [Sample depth, result in KN/m ³]
78	SpecificGravity	Alphanumeric	[Sample depth, result in kg/m ³]; [Sample depth, result in kg/m ³]
79	MaximumDryDensity	Alphanumeric	[Sample depth, result in KN/m ³]; [Sample depth, result in KN/m ³]
80	OptimumMoistureContent	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
81	CohesionUndrained	Alphanumeric	[Sample depth, result in Kpa]; [Sample depth, result in Kpa]
82	CohesionDrained	Alphanumeric	[Sample depth, result in Kpa]; [Sample depth, result in Kpa]
83	FrictionAngleUndrained	Alphanumeric	[Sample depth, result in degree]; [Sample depth, result in degree]

84	FrictionAngleDrained	Alphanumeric	[Sample depth, result in degree]; [Sample depth, result in degree]
85	LoadbearingCapacity	Alphanumeric	[Sample depth, result in Kpa]; [Sample depth, result in Kpa]
86	PermeabilityBehavior	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
87	PwaveVelocity	Alphanumeric	[Sample depth, result in m/s]; [Sample depth, result in m/s]
88	Resistivity	Alphanumeric	[Sample depth, result in Ohm-m]; [Sample depth, result in Ohm-m]
89	SwaveVelocity	Alphanumeric	[Sample depth, result in m/s]; [Sample depth, result in m/s]
90	AirVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
91	BouldersVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
92	ClayVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
93	CobblesVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
94	ContaminantVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
95	FillVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
96	GravelVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
97	OrganicVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
98	RockVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
99	SandVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
100	SiltVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]

101	WaterVolume	Alphanumeric	[Sample depth, result in m ³ or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
102	AngleOfDilation	Alphanumeric	[Sample depth, result in degree]; [Sample depth, result in degree]
103	ModulusOfElasticity Undrained	Alphanumeric	[Sample depth, result in Mpa]; [Sample depth, result in Mpa]
104	ModulusOfElasticity Drained	Alphanumeric	[Sample depth, result in Mpa]; [Sample depth, result in Mpa]
105	CompressiveStrength	Alphanumeric	[Sample depth, result in Mpa]; [Sample depth, result in Mpa]
106	ShearStrength	Alphanumeric	[Sample depth, result in Kpa]; [Sample depth, result in Kpa]
107	TensileStrength	Alphanumeric	[Sample depth, result in Kpa]; [Sample depth, result in Kpa]
108	PoissonsRatio	Alphanumeric	[Sample depth, result]; [Sample depth, result]
109	CoefficientOfVolume Compressibility	Alphanumeric	[Sample depth, result in cm ² /kg]; [Sample depth, result in cm ² /kg]
110	CoefficientOfConsolidation	Alphanumeric	[Sample depth, result in m ² /min]; [Sample depth, result in m ² /min]
111	Porosity	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
112	PHValue	Alphanumeric	[Sample depth, result]; [Sample depth, result]
113	ChlorideContent	Alphanumeric	[Sample depth, result]; [Sample depth, result]
114	SulphateContent	Alphanumeric	[Sample depth, result]; [Sample depth, result]
115	HorizontalPermeability	Alphanumeric	[Sample depth, result in m/s]; [Sample depth, result in m/s]
116	VerticalPermeability	Alphanumeric	[Sample depth, result in m/s]; [Sample depth, result in m/s]
117	GrainSizeAnalysis	Alphanumeric	[Sample depth, (sieve size,% retained), (sieve size,% retained)...
118	In-Situ Test Results		
119	NValue	Alphanumeric	[Sample depth, result]; [Sample depth, result]
120	SPTCorrectedNValue	Alphanumeric	[Sample depth, result]; [Sample depth, result]
121	ConePenetrationTest	Alphanumeric	[From depth, to depth, soil behaviour type]; [From depth, to ...]
122	SoilPercolationTesting	mm/hr	
123	MackintoshProbes	Blows.mm	
124	HandVane	Kpa	
125	PocketPenetrometer	Kpa	

126	CaliforniaBearingRatio	%	
127	Rock layer data		
128	Rock layer description		
129	RockLayerIdentifier	Alphanumeric	BoreholeName-R-layer number-latitude-longitude-level (absolute values, keep decimals, omit decimal points) e.g. BH1-R-2-33889641-35470461-6052 (mandatory field)
130	RockType	Text	Sandstone, Mudstone, Limestone ... (mandatory field)
131	RockFromDepth	m	(mandatory field)
132	RockToDepth	m	(mandatory field)
133	RockColour	Text	(Lightness, Chroma, Hue): Light Reddish Brown
134	WeatheringCondition	Text	Unweathered
135	StrengthCondition	Text	Weak, medium strong, strong ...
136	DiscontinuityDescription	Text	Roughness, aperture, infilling, Termination type, seepage
137	DiscontinuitySpacing	Text	Wide, medium, close ...
138	DiscontinuityAngleOfIncidence	Degree	Relative to the horizontal
139	DiscontinuityFrequency	No./m	Number per meter of core
140	Structure	Text	Larger-scale inter-relationship of textural features and lithology
141	Texture	Alphanumeric	The arrangement (or preferred orientation) of the grains
142	RockGrainSize	Text	Fine, medium, coarse ...
143	RockSecondaryMinerals	Text	Silicification, albitisation, pyrite ...
144	DistinctiveFeatures	Text	Discoloration, pervasive staining, or other notable features
145	TotalCoreRecovery	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
146	SolidCoreRecovery	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
147	RockQualityDesignation	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
148	RockAdditionalRemarks	Alphanumeric	
149	Laboratory Test Results		
150	RockMoistureContent	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]

151	RockBulkWeightDensity	Alphanumeric	[Sample depth, result in KN/m3]; [Sample depth, result in KN/m3]
152	RockUnitWeight	Alphanumeric	[Sample depth, result in KN/m3]; [Sample depth, result in KN/m3]
153	RockSpecificGravity	Alphanumeric	[Sample depth, result in kg/m3]; [Sample depth, result in kg/m3]
154	RockCohesionUndrained	Alphanumeric	[Sample depth, result in Kpa]; [Sample depth, result in Kpa]
155	RockCohesionDrained	Alphanumeric	[Sample depth, result in Kpa]; [Sample depth, result in Kpa]
156	RockFrictionAngleUndrained	Alphanumeric	[Sample depth, result in degree]; [Sample depth, result in degree]
157	RockFrictionAngleDrained	Alphanumeric	[Sample depth, result in degree]; [Sample depth, result in degree]
158	RockLoadbearingCapacity	Alphanumeric	[Sample depth, result in Kpa]; [Sample depth, result in Kpa]
159	RockPermeabilityBehaviour	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
160	RockPwaveVelocity	Alphanumeric	[Sample depth, result in m/s]; [Sample depth, result in m/s]
161	RockResistivity	Alphanumeric	[Sample depth, result in Ohm-m]; [Sample depth, result in Ohm-m]
162	RockSwaveVelocity	Alphanumeric	[Sample depth, result in m/s]; [Sample depth, result in m/s]
163	RockAirVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
164	RockBouldersVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
165	RockClayVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
166	RockCobblesVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
167	RockContaminantVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
168	RockFillVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
169	RockGravelVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]

170	RockOrganicVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
171	RockRockVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
172	RockSandVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
173	RockSiltVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
174	RockWaterVolume	Alphanumeric	[Sample depth, result in m3 or %]; [depth, result]... (Add unit to result) e.g.: [2, 5 %]; [6, 2%]
175	RockAngleOfDilatation	Alphanumeric	[Sample depth, result in degree]; [Sample depth, result in degree]
176	RockModulusOfElasticityUndrained	Alphanumeric	[Sample depth, result in Mpa]; [Sample depth, result in Mpa]
177	RockModulusOfElasticityDrained	Alphanumeric	[Sample depth, result in Mpa]; [Sample depth, result in Mpa]
178	RockCompressiveStrength	Alphanumeric	[Sample depth, result in Mpa]; [Sample depth, result in Mpa]
179	RockShearStrength	Alphanumeric	[Sample depth, result in Kpa]; [Sample depth, result in Kpa]
180	RockTensileStrength	Alphanumeric	[Sample depth, result in KN/m2]; [Sample depth, result in KN/m2]
181	RockPoissonsRatio	Alphanumeric	[Sample depth, result]; [Sample depth, result]
182	RockCompressibility	Alphanumeric	[Sample depth, result in 1/psi]; [Sample depth, result in 1/psi]
183	RockPorosity	Alphanumeric	[Sample depth, result in %]; [Sample depth, result in %]
184	RockPHValue	Alphanumeric	[Sample depth, result]; [Sample depth, result]
185	RockChlorideContent	Alphanumeric	[Sample depth, result]; [Sample depth, result]
186	RockSulphateContent	Alphanumeric	[Sample depth, result]; [Sample depth, result]
187	RockHorizontalPermeability	Alphanumeric	[Sample depth, result in m/s]; [Sample depth, result in m/s]
188	RockVerticalPermeability	Alphanumeric	[Sample depth, result in m/s]; [Sample depth, result in m/s]
189	RockGrainSizeAnalysis	Alphanumeric	[Sample depth, (sieve size,% retained), (sieve size,% retained)...
190	In-Situ Test Results		
191	Rock_PercolationTesting	mm/hr	

192	SchmidtHammer	R	Average rebound index
193	Water layer data		
194	WaterLayerIdentifier	Alphanumeric	BoreholeName-W-layer number-latitude-longitude-level (absolute values, keep decimals, omit decimal points) e.g. BH1-W-3-33889641-35470461-6052 (mandatory field)
195	WaterFromDepth	m	(mandatory field)
196	WaterToDepth	m	(mandatory field)
197	WaterColour	Text	
198	WaterOdour	Text	
199	WaterPressure	Pa	
200	ColiformBacteria	Text	Positive or Negative
201	Nitrates	mg/L	
202	WaterPH	Number	
203	Alkalinity	mg/L	
204	Sodium	mg/L	
205	WaterChloride	mg/L	
206	Fluoride	mg/L	
207	WaterSulphate	mg/L	
208	Iron	mg/L	
209	Manganese	µg/L	
210	TotalDissolvedSolids	mg/L	
211	TotalSuspendedSolids	mg/L	
212	Hardness	mg/L	
213	Arsenic	mg/L	
214	Selenium	µg/L	
215	Uranium	mg/L	
216	PesticideContamination	True/False	
217	MethyleneBlueActiveSubstances	mg/L	
218	Strontium	mg/L	
219	Methane	mg/L	
220	Radium	pci/L	
221	BTEX	ppb	Benzene, Toluene, Ethyl- benzene and Xylene.
222	Bromide	mg/L	
223	Barium	mg/L	

224	AnnualRange	Alphanumeric	Indicative (95%-100%) annual range in levels.
225	AnnualTrend	Alphanumeric	Indicative (95%-100%) annual rise in level.
226	IsFreshwater	True/False	Indication of freshwater (True,False or n/a)
227	Temperature	°C	
228	Conductivity	S/m	
229	WaterFlow	L/s	
230	DissolvedOxygen	mg/L	
231	Calcium	mg/L	
232	Magnesium	mg/L	
233	Potassium	mg/L	
234	Carbonate	mg/L	
235	Bicarbonate	mg/L	
236	Lead	mg/L	
237	Silica	mg/L	
238	Ammonia	mg/L	
239	Orthophosphate	mg/L	
240	Phosphorus	mg/L	
241	TotalOrganicCarbon	mg/L	
242	DissolvedOrganicCarbon	mg/L	
243	Antimony	µg/L	
244	Vanadium	µg/L	
245	Beryllium	µg/L	
246	Boron	µg/L	
247	Cadmium	µg/L	
248	Chromium	µg/L	
249	Cobalt	µg/L	
250	Copper	µg/L	
251	Lithium	µg/L	
252	Molybdenum	µg/L	
253	Nickel	µg/L	
254	Strontium	µg/L	
255	Thallium	µg/L	
256	Void layer data		
257	VoidLayerIdentifier	Alphanumeric	BoreholeName-V-layer number-latitude-longitude-level (absolute values, keep decimals, omit decimal points) e.g. BH1-V-4-33889641-

			35470461-6052 (mandatory field) (mandatory field)
258	VoidFromDepth	m	(mandatory field)
259	VoidToDepth	m	(mandatory field)