# Geological Data Extension for Subway Tunnel BIM models using a Linked Data Approach

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## Summary

The urbanization process is being accelerated in developing countries and rural areas near the metropolis like Peking or Shanghai face developments. Infrastructures that facilitate the transportation are the precondition for such development. Metro systems as high capacity public transport facilities link the remote rural area to urban area with low cost. Thus, how to make use of metro design and construction as a vital information source to facilitate the operation process regarding disturbance monitoring caused by nearby construction activities and to efficiently disseminate geological data for future re-use in residential and commercial developments design becomes a concern. As a subtype of underground structure, Metro tunnels exhibit many similarities and differences with building structures above ground. They both involve many stakeholders and disciplinary, and these ask collaborative work and information exchange effectively. But the underground structures required higher efficiency in design, construction and operation due to a. massive investment at early stages; b. more difficulties during the construction (complicated geological condition, other infrastructure facilities underground); c. longer construction period; d. more involved stakeholders and more complicated information. All these differences demand much more money, time and manpower to deal with. Therefore, reusing existing information tends to be necessary. The Semantic Web is conceived to facilitate information linking, sharing and reusing across applications, and organization boundaries. Linked Data, which lies at the heart of the Semantic Web, is able to make the Semantic Web a reality through creating interrelated data (W3C, 2015). Building Information Modelling is frequently used to integrate building data through life cycle and other disciplines. The Industry Foundation Classes (IFC) data model is intended to describe building and construction industry data. It is a platform neutral, open file format specification that is not controlled by a single vendor or group of vendors. It is an object-based data model developed by the buildingSMART organization (formerly the International Alliance for Interoperability, IAI) to facilitate interoperability in the architecture, engineering and construction (AEC) industry, and is a commonly used collaboration format in building information modeling based projects (buildingSMART, 2016). When applying the BIM methodology to subway systems, *IFC-ShieldTunnel* has been an obvious first step, as shield tunnels are the most common structural form for metro tunnels. However, concerning the geological information domain, *IFC-ShieldTunnel* attempted to cover geo-test information but was incapable of accomplishing it so far (Yabuki et al, 2013; Amann et al, 2013). Since there is existing experience in extending IFC-ShieldTunnel and processing sensor data with Semantic Web technologies (Eid et al.; 2007; Sheth et al., 2008; Bamaghi et al., 2009; Janowicz et al., 2010; Smart Appliances, 2013), these previous researches imply that Linked Data approach could bring advantages to extend BIM model with geological data.

In this thesis, a survey of information requirements related to geological data for underground structures is conducted; and suitable proposals to extend the semantics of such models are developed. A comprehensive comparison among common IFC extension mechanisms based on a literature review is given. Moreover, a Linked Data approach is

proposed to integrate geological sensor data into metro tunnel BIM models for project managers' monitoring and other designers' referencing demands. The report is structured into 6 chapters to clarify and verify the geological data extension process and method. Chapter 1 discusses the research backgrounds, research design, research questions. Chapter 2 is the glossary of the thesis. Chapter 3 holds the literature review of the current researches on Ifc-ShieldTunnel, Ifc extension mechanisms currently used to extend infrastructure model, the Semantic Web and its application. Chapter 4 introduces the geological data extension using ifc property set extension, extension mechanisms comparison and methodology to apply Linked Data integrated geological data and BIM model. Chapter 5 documents the prototypical implementation of this methodology through a case study of Dongjing Station, an actual project from Shanghai metro design institute. In the end, chapter 6 offers some discussion regarding the whole extension and points out a few future research recommendations.

The methodology of this extension research process is divided into seven parts. The main flow path of the extension is literature study, collecting data, analyzing data, transforming and merging data, linking data, querying data and converting according data visualization. These technical steps are examined through the case study, and several query result visualizations are shown to guarantee facilitating design and construction process for project managers.

In the case study, there are five different sources obtained from Shanghai Metro Design Institute. Through the Linked Data approach, serialize the data structure and merge them into an RDF model, which are apparently of easy to process and query extended data synthetically regardless of domain boundaries. It is validated that applying the Linked Data approach to extend BIM model with geological data is an effective way to achieve the Ifc-ShielfTunnel extension.

## Abstract

Geological survey data is vital throughout the life cycle of a tunnel; not only as information supporting project operation but also a useful reference for newly developed buildings surrounding the projects. However, this important information is not made well use of in metro tunnel projects due to missing in situ geological information regarding Ifc-ShieldTunnel. This thesis investigates the required information about geological survey data for shield tunnels and extends Ifc-ShieldTunnel with IFC property sets that can be attached to IfcCivilGeologyElement abstract entity under IfcCivilElement entity. However, such extension mechanism relies on IFC schema too much to actually provide means for data reuse. In order to work around that, a Linked Data approach that is able to extend BIM models from various sources regardless of exchange format or domain boundaries, provides both project managers and designers a flexible way to make use of relevant geological survey data. A case study is conducted at the end of the thesis to verify the extension.

# 1 introduction

In the tunnel engineering field, shield tunneling is one of most typical tunnel construction methods which is applied in soft soil area such as all the metro tunnels in shanghai. With the development of modern shield tunneling technology and crafts, considering soil condition as a precondition of applying shield tunneling is being more flexible, in other words, more and more shield tunnel would be designed and constructed. Until the end of 2014, the Shanghai Metro Company got 548 Km metro line under operating, which is about 35% passenger flow of public transportation in shanghai (Wu, 2015). Based on Shanghai railway transportation planning, there would be mileage of 700 Km under operating in 2018, and 800Km in 2020, whereas, almost all of the metro tunnels are the shield tunnels.

As an important category of underground structure, shield tunnels have a lot of similarities and differences with building structures above ground. In which, it is similar to other building above the ground since the whole process involves a certain number of departments and difference expertise which would require the collaborative work and information exchange. And it differs from those buildings due to its massive investment at an early stage, more difficulties during the construction process (complicated geological condition, other infrastructure facilities underground), longer construction periods (several years usually), more involved stakeholders and more complicated information. In addition, after delivering the project to the client, to ensure the safety and reliability of shield tunnel structure, metro companies spend a lot of resources to maintain it. To improve the construction management level and project quality of underground engineering under complicated circumstances, it is quite necessary to conduct research regarding up to date information technology such as building information modeling (BIM) applying in the shield tunnel engineering.

BIM technology states that one BIM is an acronym for Building Information Modelling. BIM describes the means by which everyone can understand a building through the use of a digital model which draws on a range of data assembled collaboratively, before during and after construction. Creating a digital Building Information Model enables those who interact with the building to optimize their actions, resulting in a greater whole life value for the asset (John et al, 2013). And the Industry Foundation Classes (IFC) data model is intended to describe building and construction industry data. It is a platform neutral, open file format specification that is not controlled by a single vendor or group of vendors. It is an object-based file format with a data model developed by buildingSMART (formerly the International Alliance for Interoperability, IAI) to facilitate interoperability in the architecture, engineering and construction(AEC) industry, and is a commonly used collaboration format in building information modeling based projects. The current IFC standard managed to describe building project throughout life cycle in a great manner, but fail to cover the route infrastructure such as shield tunnel. Froese (2003) referred that the scope of the IFCs should be extended beyond buildings to include a broad range of civil infrastructure, to address interoperability for projects such as road building, underground utility maintenance, or bridge construction, it would be reasonable to extend the IFC model to include these types of projects within their scope.

Geological data is an important dataset for building management during operation phase, especially buildings underground. Since the geological data can be a shared dataset due to its location, it could be referenced by other building projects both above ground and underground. With the geological data, operation personnels are able to control structural disturbance caused by other buildings' construction, also the designers for surrounded building could reuse the geological data to optimize design process efficiently.

To achieve that, the Linked Data is brought into integration as one of the most promising strategies. It managed to integrate separate data derived from diverse authoring tools in a Resource Description Framework (RDF) format (Pauwels, 2014). So that, the geological data can be combined with BIM, which makes all the building related data that are even out of BIM model easier to incorporate with more buildings, for the purpose of facilitating operations and design.

Within this research, an attempt of extending BIM model with both IFC propertyset extension and the Linked Data approach in order to reuse geological data for design and operation is developed. And it is verified via a case study which could suite Shanghai Metro Design institute's requirements.

## 1.1 Problem definition

Geological data is always important for a building project and it has influence throughout life cycle, for instance, in the early stage, geological data is a decisive factor, designers cannot even start their design without the thorough geological related information investigation; in the operation stage, the geological data changing would cause structural damage. Especially for the underground structure such as a metro tunnel, it relies on the geological data even more.

However, there are also many stakeholders involved in geological data exploration due to its complexity. The dataset is made of plenty data files with multiple sizes and data formats. Currently, the IFC 4 has not contained all these related information for infrastructures, not even mention specifically for shield tunnels. This missing part of BIM model costs extra attention such as money and time to these data so that manager could ensure building operation runs smoothly. What is worse, this extra resource consumption for the building project itself is inevitable; but for other surrounding buildings, they will not be able to reuse this related geological information well which makes the BIM model became a not "shared model" due to its complexity. Naturally, the property of non-referential cost unnecessary but inevitable resources.

To solve the problem, an extended IFC-ShieldTunnel model needs to be explored based on both buildingsmart framework and geological engineering handbook. The proposed model would indicate what information is required and how they organized under IFC frame. Though, the extension can be made based on IFC frame. There are still limitations since BIM and IFC have the inherent weakness regarding storing cross sources information. In this case, a comprehensive comparison among common extension mechanisms required to be explored, particularly in terms of geological data. Even a certain mechanism is best to solve problems theoretically; whether it will behave excellence should be verified.

## 1.2 Research questions

Extending shield tunnel BIM model with geological data enables project managers and other designers get a holistic view of building operation and design. Linking geological conditions with the structural properties of the building offers managers a proof to make quick decisions in advance, as well as providing a reference for other designers who will work on develop building surround the existing project. In this research, BIM and IFC format are used to represent metro station. The possibility to extend the BIM model is explored.

Main question:

- How to extend shield tunnel BIM models with geological data in order to optimize the operation phase and design process by reusing existing geological survey data?

Sub question

- What geological data is required for shield tunnel BIM models?
- How to integrate required information with IFC?
- What are the common extension mechanisms for BIM models? How do they behave in terms of a geological data extension?
- Which method is the most appropriate approach in the case of a geological data extension for shield tunnel BIM models?

## 1.3 Research design

The whole research design is made of five parts, as shown in figure below.

The research begins with IFC standard study, from IFC to IFC structure then to IFC-Shield Tunnel. Afterwards, the survey to sort out what kinds of geological data are required for shield tunnel is conducted. Later on, extending the BIM model with survey outcome under buildingsmart framework is completed. Part 4 introduces the common extension mechanisms and then assesses them in the case of geological data application. Part 5 applies the most appropriate extension mechanism to the geological data extension for shield tunnel in the actual case.

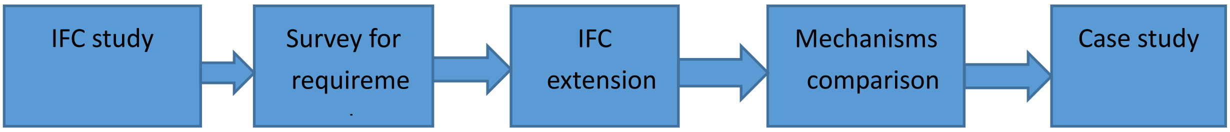


Figure 1 Research process

## 1.4 Expected results

This research sorts out the required geological information set for shield tunnel, and then extends these information in IFC standard. It also offers the comprehensive comparison among common extension mechanisms. Moreover, this research verifies the assessment-defined appropriate approach through a case study.

## 2. Glossary

This chapter represents a summary of the most important definitions, notion, classifications, etc related to shield tunnel BIM model extension regarding geological data.

**AEC**: The abbreviation for sector of the construction industry that provides the services on the architectural design, engineering design and construction services..

**Building Information Modelling (BIM)**: A process involving the generation and management of digital representations of physical and functional characteristics of places.

**Drill Hole:** A hole made by a drill, usually made for exploratory measurements.

**Shield Tunnel:** A protective structure used in the excavation of tunnels through soil that is too soft or fluid to remain stable during the time that it takes to line the tunnel with a support structure of concrete, cast iron, or steel.

**EXPRESS**: A standard data modelling language for product data.

**Resource Description Framework (RDF)**: A standard model for data interchange on the web.

**Linked Data**: A set of best practices for publishing structured data on the web.

**buildingSMART**: A worldwide authority driving the transformation of the built asset economy through creation and adoption of open, international standards.

**Ontology Web Language (OWL)**: A family if knowledge representation language for authoring ontologies.

**Uniform Resource Identifier (URI):** A string of characters used to identify a resource.

**Turtle (syntax):** A format expressing data in the RDF model.

**International Alliance for Interoperability (IAI):** is an international organization which aims to improve the exchange of information between software applications used in the construction industry, now known as buildingSMART.

**SPARQL:** An RDF query language.

**Ontology:** A philosophical study of the nature being, becoming, existence, or reality as well as the basic categories of being and their relations.

**Smart Appliances REFerence (SAREF):** is a shared model of consensus that facilitates the matching of existing assets (standards/protocols/datamodels/etc.)

**Extensible Markup Language (XML):** A simple, very flexible text format derived from SGML (ISO8879).

**Geosensor:** A sensor to explore geophysical and geotechnical features.

**North east down:** A geographical coordinate system for representing state vectors that is commonly used in aviation

**Geocentric rectangular coordinates:** A coordinate system take earth as a sphere or a rotating ellipsoid in a right-handed XYZ coordinate system (3D Cartesian) measured from the center of the earth.

# 3. Literature review

In the BIM perspective, making a comprehensive shield tunnel BIM model which contains all the information and data related to all the expertise, for instance, geotechnical engineering, structural engineering, rail engineering, MEP, etc. would undoubtedly be a complicated and tremendously huge task. When doing research on making standard, a practical research method is that aiming at a certain application field, elaborate research on one or several closely linked fields. The key of applying BIM concept to shield tunnel engineering is integrating all information throughout life cycle in order to achieve collaboration and information exchange among the different stages, departments and expertise. However, existing BIM related standard has not cover shield tunnel engineering completely. As a result, project manager felt quite inconvenient when they operate the metro shield tunnel structure since the lack of uniform geology related information.

In this chapter, current studies in the fields of IFC, IFC-ShieldTunnel, geological information requirements, IFC-ShieldTunnel extension with geological data is introduced. Afterwards, studies on ad-hoc extension mechanism, solely proxy extension, XML extension, Linked Data extension are conducted. Brief theoretical comparison among these extension mechanisms is discussed.

## 3.1 IFC introduction

The essence of BIM technology is information exchange and share. And the most basic approach to achieve information exchange and share would adopt a uniformed international data exchange standard. At the present stage, Industry Foundation Classes, IFC is the most comprehensive, object orientation data standard in the AEC industry (Shi, 2014), also known as accepted BIM data description and exchange standard (IUG/DMG, 2010)..

IFC is an open, neutral standard. The main purpose of adopting IFC standard are the following two points: firstly, support information exchange and share through the whole life cycle of project. Secondly, support information exchange and share in the different domain, not only for the certain specific domain. BuildingSMART is responsible to conduct research and released them. The first official version is IFC1.0 at Jan 1997, which built the basic frame theory. After that, building released several versions of IFC standard, mainly for amination, validation and extension of standard (Dai et al, 2007). The development of IFC standard is shown in the Figure 2 (Ming, 2014).

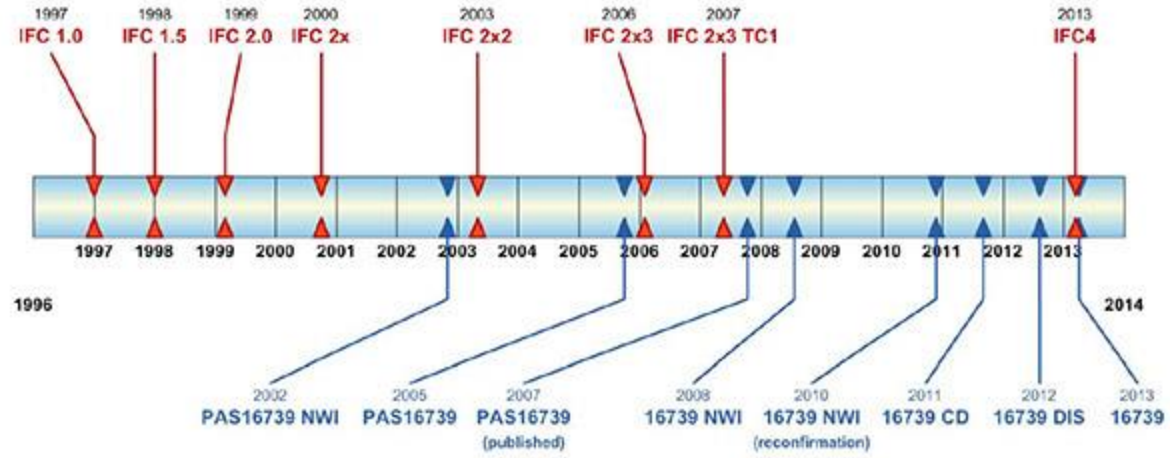


Figure 2 the development of IFC standard (Ming, 2014)

### 3.1.1 Fundamental technical aspects and structure of the IFC data model

Using existing parts from the ISO STEP standard, most notably incorporating concepts from the BCCM model, EXPRESS modeling language, definitions for geometric representation, technical development did not begin from an empty slate (Eastman, 1999) (IAI, 1999) estimates that about half of the objects and types present in the first IFC releases were adopted from the integrated resources of STEP. Nevertheless, the task of composing a strict but flexible data model capable of containing and representing product and process data fulfilling the requirements of an entire industry is no small task. Information modeling involves the extraction and subjective interpretation of reality, defining concepts and attributes considered relevant and creating semantic relationships between them. Thus, creating an unambiguous internationally accepted generic data structure is an extremely challenging task. IFC was always intended to be a high-level data model, like STEP, which exists above software implementations to remain truly neutral and future-proof. It provides a standardized data structure for the storage of building information, but does not it enforce, or even enable, any specific way of implementing it into software. Almost anything is possible; it is up to the software developers to decide. EXPRESS schemas containing IFC data can be encapsulated into files for physical file-based exchange, or the IFC data structure can be represented in an object-oriented database and be updated remotely over the Internet In practical terms, most BIM software end-users interface with the IFC in the 'Save As' or 'Export' dialogue of the software where the IFC standard might be listed as one of the options for storing the model data, in parallel with proprietary data formats. However, the IFC standard itself is not an API (Application Programming Interface), though some have argued that it is rather, the IFC standard is a generic implementation-independent data model along which APIs can, and have been, designed to implement the data model in different application environments and programming languages (FP, 1999). The structure of the IFC data model was divided into four layers: domain, interoperability, core, and resource layers. Relationships between these layers appear in Figure 3. The layers have strict referencing hierarchies, the main rule of thumb being that referencing can only occur downwards in the hierarchy. This means that data in the resource layer must be independent and reference no classes above it. The other layers, however, can all reference data from the resource layer as well as all other layers below them. References within the same layer are allowed only for the resource layer. The resource layer holds the resource that contains basic definitions intended for describing objects in the above layers. The core layer consists of the kernel and extension modules. The kernel determines the model structure and decomposition, providing basic concepts regarding objects, relationships, type definitions, attributes and roles. Core extensions are specializations of classes defined in the Kernel. The interoperability layer provides the interface for domain models, thus providing an exchange mechanism for enabling interoperability across domains. The domain layer contains domain models for processes in specific AEC domains or types of applications, such as architecture, structural engineering, and HVAC, among others (IAI,1999), (IAI,2000).

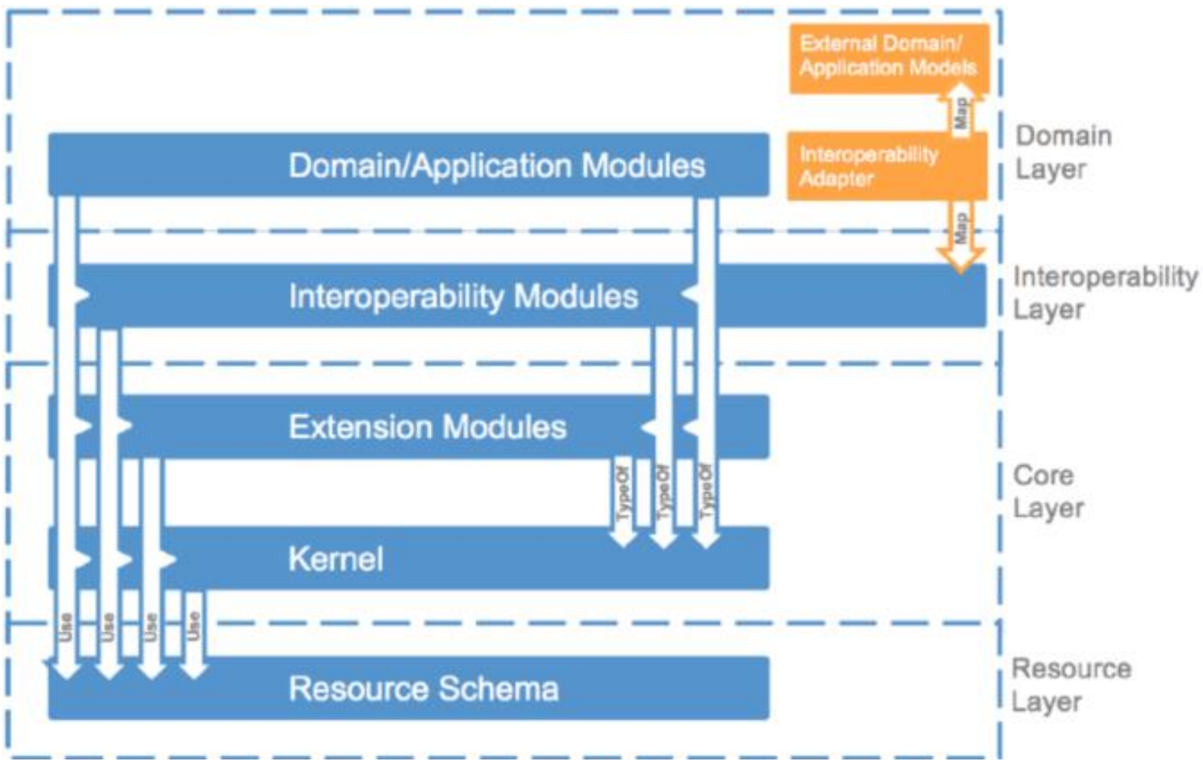


Figure 3 structure of IFC 4 data model (IAI,1999), (IAI,2000)

### 3.1.2 IFC extension

As an open source international standard system, IFC supposed to kept updating continuously due to industry features and requirements. However, AEC industry differs from regional difference, object diversity, information complexity and etc, Current IFC 4 failed to contain all the information. As a consequence, IFC standard offered multiple extension method so that related researchers would be able to extend IFC by following its data structure. For now, there are mainly three mechanisms to extend the IFC (Wang, Zhang, & Li, 2014): IfcProxy extension, IFC entity extension, IfcPropertySet extension.

**IfcProxy extension**

The IfcProxy is intended to be a kind of a container for wrapping objects which are defined by associated properties, which may or may not have a geometric representation and placement in space. A proxy may have a semantic meaning, defined by the Name property, and property definitions, attached through the property assignment relationship, which definition may be outside of the definitions given by the current release of IFC.The ProxyType may give an indication to which high level semantic breakdown of object the semantic definition of the proxy relates to. The Tag property may be used to assign a human or system interpretable identifier (such as a serial number or bar code) (IfcProxy, 2016). It is in the core layer, an entity type can be instantiated, not to a specific object. And it inheritance graph is shown in Figure 4. Researchers could set ProxyType and Tg by instantiating IfcProxy, and describe the self-defined object with PropertyType and optional geometry information. Within it, ProxyType is IfcObjectTypeEnum data, which can be defined as geometry, process, control, resource, manpower, item and tec., Tag is used to describe self-defined property.

When using IfcProxy extension mechanism, it is possible to appear “repeat” IfcProxy object description, but after adopting IfcProxy property information judgement, users would be able to identify different type of self-defined object. With this extension mechanism, it could be compatible to existing IFC tools, and relatively small changes to the IFC model frame, but low running efficiency (Zhang, 2009).

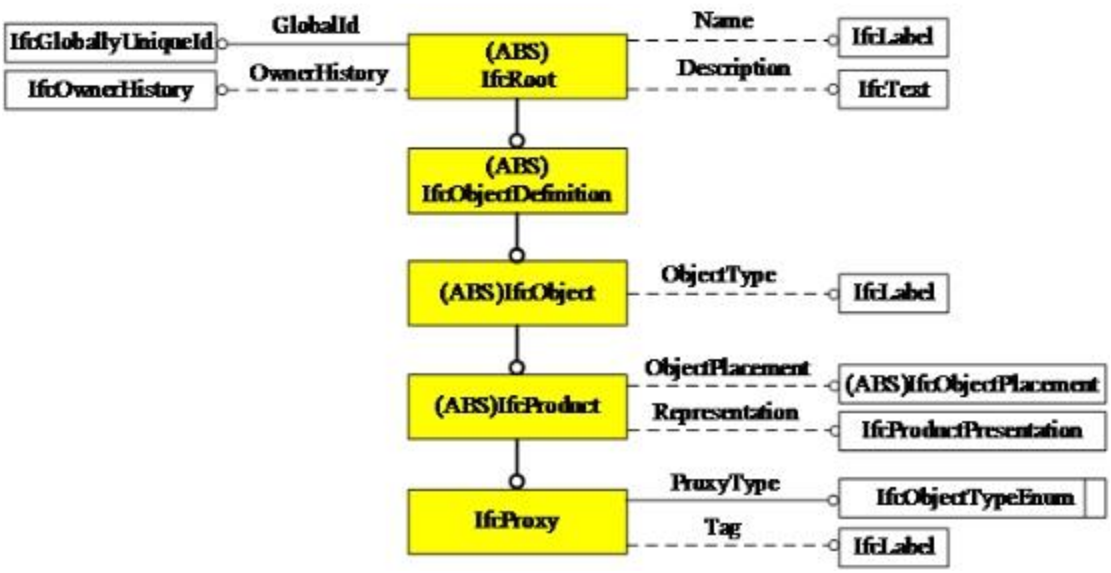


Figure 4 ifcProxy inheritance (buildingSMART, 2016)

## IFC Entity extension

In an IFC model, the project information (generated, for example, from an ArchiCAD project) is represented as a set of IFC Entities – such as elements, surfaces, and their relationships. Each IFC Entity (for example, an IfcWall) includes a fixed number of IFC Attributes, plus any number of additional IFC Properties. The IFC scheme encompasses several hundred entities, of which the building element-type entities (such as IfcWall and IfcColumn) represent only 25 (GRAPHISOFT, 2015), and it is shown in the Figure 5

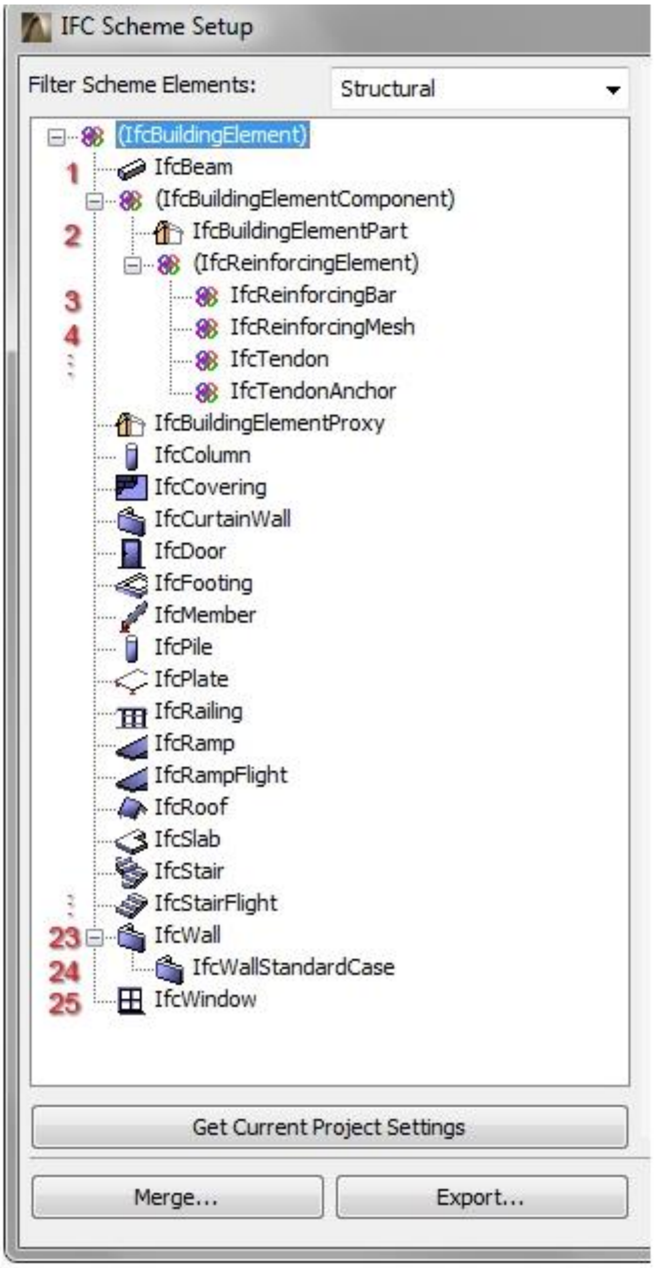


Figure 5 building element-type entities Error! Reference source not found.

Compared with IfcProxy, entity extension mechanism is difficult to execute, it required to follow the rules and procedure made by standard management organizations. However, its advantages of such good data encapsulation and high running efficiency make itself adopted on IFC standard version updating. IFC entity extension can be classified into expanding of IFC entity and expanding of IFC entity property (Wang et al, 2014).

The versions before IFC2x4 fail to cover line-type project. Till IFC2x4 version released, IfcCivilElement entity is added. Unlike other well developed building element described with

IfcBuildingElement entity, IfcCivilElement is specifically defined for line-type project description, such as road, bridge, tunnel and etc. Their inheritance relation is shown in the Figure 6.

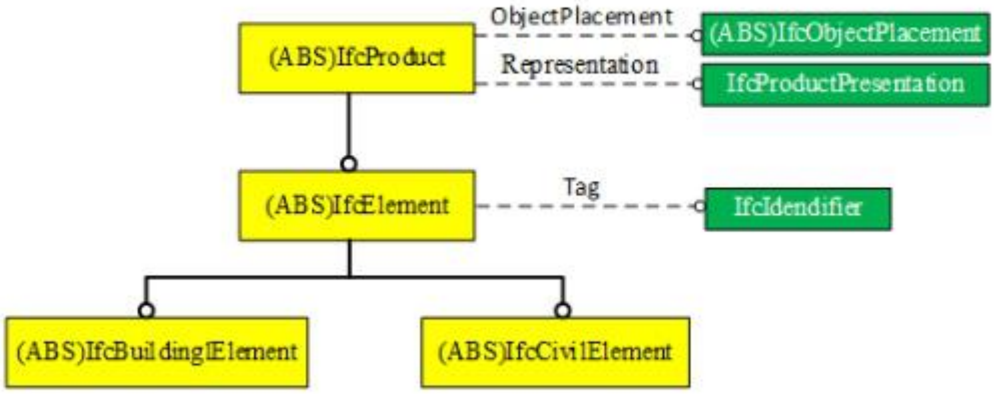


Figure 6 IFC 2x4 added IfcCivilElement entity (buildingSMART, IfcProductExtension, 2016)

Noticeably, when using expanding of IFC entity mechanism, the derived relations and association between new entities and existing entities must be clearly set in case model frame get conflict and ambiguity.

IFC entity property expanding refers, build on IFC entity, and adjust entity property including: adding, modifying and deleting. BuildingSMART would use this extension mechanism often when updating IFC standard. Nevertheless, the mechanism is limited by expanding range, used as auxiliary extension approach.

**IfcPropertySet extension**

IfcPropertySet defines all dynamically extensible properties. The property set is a container class that holds properties within a property tree. These properties are interpreted according to their name attribute. The same IfcPropertySet can be assigned to multiple object occurrences; it should then be assigned by a single instance of IfcRelDefinedByProperties to a set of related objects. Those property sets are referred to as shared property sets. It can also be assigned to an object type. An IfcPropertySetTemplate may define the underlying structure, i.e. the required name, the applicable object or object types to which the property set can be attached, and the individual properties that maybe included. Compared with IFC entity extension, IfcPropertySet extension is more flexible and would not tamper IFC model structure which implies it is more advanced. There are three parts of information included in the property set, property set name, applicable entities and applicable type value, definition. Its template is shown in the Table 1 below.

Table 1 IfcPropertySetTemplate

| | |
|---|---|
| Property Set Name | |
| Applicable Entities | |

| Applicable Type Value | | | | |
|---|---|---|---|---|
| Definition | | | | |
| Property Name | Property Type | Data Type | Unit | Definition |
| | | | | |

### 3.1.3 Existing Ifc-ShieldTunnel

Amann et al describe a generalized IFC 4 based alignment model that can be used in the field of infrastructure to describe road, tunnel and bridge alignments. The model supports a 3D space curve (IfcReferenceCurve3D) as well as the traditional approach of horizontal and vertical alignments (IfcReferenceAlignment2D) (Amann et al, 2013). The IfcReferenceAlignment2D consists of a gap and junction free horizontal (IfcHorizontalAlignment) and vertical alignment (IfcVerticalAlignment). The IfcHorizontalAlignment consist of an ordered list of IfcHorizontalAlignmentSegments. An IfcHorizontalAlignmentSegment is a superclass of IfcHorizontalAlignmentLine for line segments, IfcHorizontalAlignmentCircularSegment for circle segments and IfcHorizontalAlignmentTransitionCurve for transition curves. The only supported transition curve is the IfcHorizontalAlignmentClothoid for a clothoid. The vertical alignment consists of an ordered list of IfcVerticalAlignmentSegments such as IfcVerticalAlignmentPointVerticalIntersection and IfcVerticalAlignmentRounding. An IfcVerticalAlignmentRounding has only one subclass (IfcVerticalAlignmentParabola). Instead of introducing new geometry representations for elements like straight lines or arcs, it references new geometry using existing geometry representations from the IFC. In particular, the extension contains the semantic elements IfcLine and IfcCircle that reference an IfcTrimmedCurve object to describe straight-line segments and arcs. The semantic line and circle object do not introduce new geometric representations to avoidduplication of geometric descriptions: the IFC already contains many different options to describe straight lines and arcs. Similarly, a clothoid element is described with a trimmed curve. Since the standard IFC does not support clothoids, an IfcHorizontalAlignmentClothoid has been introduced to hold some specific data of the clothoid such as the clothoid constant.

Several IFC based shield models have already been proposed. Japanese researcher Yabuki and his research group did most work within the field. 2005, Yabuki started BIM model regarding shield tunnel and named it IFC-ShieldTunnel. 2013, Yabuki group revised it, afterwards, it offered basic frame for IFC-ShieldTunnel. For now, IFC-ShieldTunnel research has already become a part of Infrastructure Alignment & Spatial Reference System project (P6) which is conducted by buildingSMART, and the project aimed at cover the life-cycle information of shield tunnel.

Yabuki conducts related research through shield tunnel corresponding entities and property set. The main defined information in the IFC-ShieldTunnel is listed in the Table 2 and product model as shown in the Figure 7. Nonetheless, some of defined entities in IFC-ShieldTunnel information model (Yabuki et al, 2013) just stayed on semantic.

Table 2 IFC-ShieldTunnel defined information (Yabuki et al, 2013)

| **domain** | **object** | **IFC entity** |
|---|---|---|
| Geological information | Stratum, ground water | IfcStStratumElement、IfcGroundwaterElement… |
| Tunnel elements information | Segments, water-proof material, secondary lining, working shaft and etc. | IfcStTunnelElement、IfcStSegmentElement、IfcStWaterProofingElement、IfcStSecondaryLiningElement、IfcStBackFillGroutingElement、IfcStJointStructureElement… |
| Other information | Shield machine, retaining wall, obstacle, service facility and etc. | IfcStShieldMachineElement、IfcStEarthRetainingWallElement、IfcStObstacleElement、IfcStServiceFacility… |

For instance, IfcStObstacleElement, an entity derived from shield tunnel physical element IfcStElement refers that underground obstacle is a type of shield tunnel physical element, but IFC-ShieldTunnel did not show the exact description of IfcStObstacleElement.

Apart from that, in the geological information domain, IFC-ShieldTunnel failed to cover test information; in the construction information, monitoring information and structure disease information field, IFC-ShieldTunnel did not elaborate it as well.

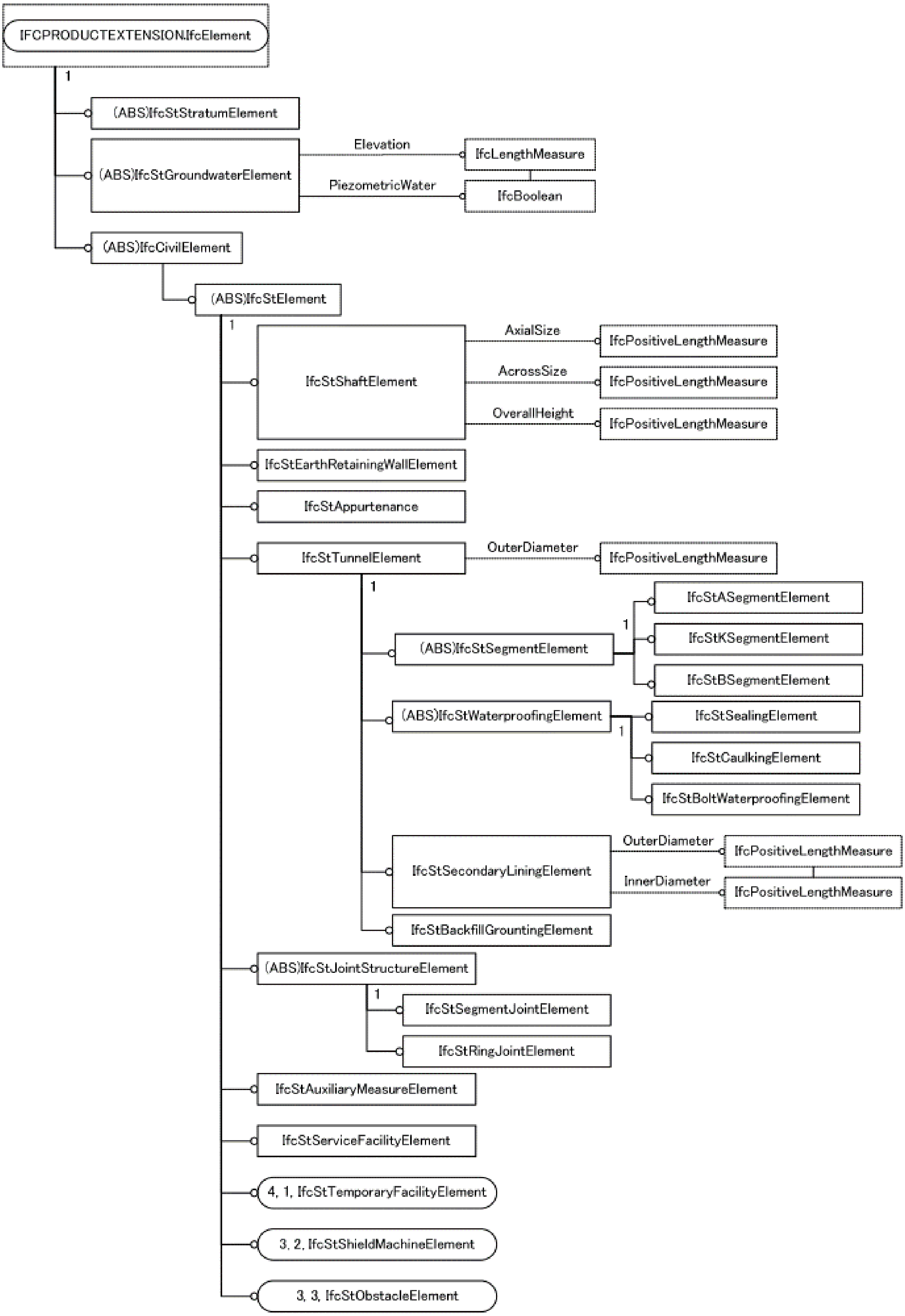

Figure 7 A part of the product model developed for shield tunnels, IFC-ShieldTunnel (Yabuki et al, 2013)

## 3.2 Geological information requirement analysis

Code for geotechnical engineering investigation of urban rail transit divided the geotechnical engineering survey into four stages: feasibility study survey, preliminary survey, detailed survey and construction survey. Feasibility study survey aims at alignment plan selection through the survey of surrounding environment, geological conditions and etc. so that could provide criteria for selection; preliminary survey based on the feasibility study, find out the accordingly geology and hydrogeology of metro stations and other related ancillary facilities to analysis the foundation type and construction method for the purpose of sorting out required geological parameters; detailed survey built on preliminary survey, investigated more details for construction design; construction survey is referring investigating some specific surveys just to satisfy the certain construction method requirements in terms of risk control and altered design.

Mentioned above four stages, they would be conducted sequentially during the project, and have their own purposes and tasks. But overall, the ultimate purpose of these stages is consistent which is ascertaining geological conditions, hydrogeological conditions, surrounding environment and etc. to provide scientific basis for further design and construction.

The outcome of geological engineering investigation could be mainly classified in three categories: geological exploration (boring hole, Stratigraphic distribution, ground water, and sampling), in situ test and laboratory test, for different categories, the information requirement is listed in the Table 3 below.

Table 3 the list of required information in the geological engineering investigation

| Category | | Subcategory | Specific required information |
|---|---|---|---|
| Geological exploration | 1 | Boring hole information | Boring hole number、coordinate、type、methodology、depth、date、backfilling method 、 backfilling material 、 Stratigraphic distribution 、 soil description、groundwater and etc.； |
| | 2 | Observation wells information | number 、 coordinate 、 elevation of borehole、hole depth、water level、water quality information 、 observation data and etc.； |
| | 3 | Sampling information | source、 sampling method、 number、 quality grade、 disturbance degree and etc.； |
| | 4 | Stratum information | Terrain stratigraphic distribution derived from drilling, in situ test and laboratory test, and its parameters of physical and mechanical |

| | | | |
|---|---|---|---|
| In situ test | 1 | Standard penetration test | |
| | 2 | Dynamic penetration test | |
| | 3 | Lateral loading test | |
| | 4 | Cone penetration test | |
| | 5 | Static loading test | |
| | 6 | Flat dilatometer test | |
| | 7 | Vane shear test | |
| | 8 | In situ shear test | |
| Laboratory test | 1 | Density test | |
| | 2 | Particle analysis experiment | |
| | 3 | Water content test | Major experimental parameters and concrete findings information |
| | 4 | Water ratio limit test | |
| | 5 | Direct shear test | |
| | 6 | Triaxial compression test | |
| | 7 | Consolidation test | |
| | 8 | Lateral earth pressure coefficient at rest test | |
| | 9 | Unconfined compressive strength test | |
| | 10 | Permeability test | |

Under three categories, there are some items accordingly, in total 22 items. The detailed required information lists for according items are sorted out and given in the appendix A.

Usually the files for documenting all information can be classified into three categories, literary description mainly expressed in the doc. File and pdf. Fille; lists, tables, charts and etc. expressed in the xls is also the source file mostly; drawings expressed in the dwg. file or dxf. file and etc. still for the presentation to the client, there are sometimes ppt. file being prepared.

**Literary description**

Massive information in the geological survey is shown in literary description, such as the project name, the purpose of project and certain test, the types of these tests, the color of stratum, evaluation of them. The conclusion of assessment along with the suggested construction plan, monitoring plan, design and etc would be given in the literary description. All the files are input by manpower who are working in the site; people who work in the lab; consultants who work in the consultancy companies. To sum up, these files are made by people from different companies as different roles in the project; by people possibly from same companies but in different working places. And the size of these files could vary from 10MB to over hundreds MB due to the complexity and required level of project. Take water level observation well as example, if the safe level is required to be quite high by clients, then probably the most cautious wells plan would be adopted, more wells could be set and more frequently the data would be collect, which indeed make literary description getting longer to keep all the needed information. Presumably, the underground water level and underground water type are not that optimistic. As a consequence, the suggested monitoring plan, design, construction plan and etc. would have to be more complicated and detailed, even the prediction and prevention of emergency plan getting necessarily detailed and sounded which obviously makes file size larger. With this principle, there are quite some parameters able to determine whether description getting longer and more complicated, for instance, client requirements, actual geological conditions, number of involved parties and even the budget of project, etc. Also, it is quite timely manner, some tests would last 12 days from the project start, some of them have to last longer, and certainly some would be shorter. Apparently, efforts need to be put on collaboration these efficiently.

**Lists, tables and charts**

As aforementioned, there are tremendous information currently expressing in the list which can formulate xls. file, the imported standards for all the tests, the ID(code) of monitoring pot, location of those samples, etc. Meanwhile, there are some figures derived from other known numbers or linked to other know ID, all these would be given in the xls file. Imaginably, at early stage the xls files are made for documentation, however, at the middle stage, extensive assessments have to conduct based on the documented information with the help of excel, furthermore, more importantly, all the assessments outcomes must be shown understandably through charts or graphs through excel as well. Like the literary description, the size of file would differ from geological conditions, client requirements and etc. But unlike literary description, the size of files varies huge due to these. It can be ranged from MB to GB. Noticeably, the source of figures in the list not are simply input by men, certainly there are some are, there are still data obtained through the monitoring equipment directly, some of them from GIS data based directly. Various sources make these lists, tables a bit more different to sort out, no need even to mention to collaborate with all those involved parties. The updating period differs from the test per se. Take zeroone foundation pit measuring and monitoring software as an example, for the huge project like a metro station of Shanghai line 14, there are over hundred megabytes' data fit in their files every daily check. And it is only in terms of foundation pit of a metro station. Plausibly assume, to conclude whole set of aforementioned data in the list, it is quite possible the size of files would spike to gigabytes.

**Drawings**

There are indeed some drawings needed to illustrate the stratum more detailed and vivid. The cross section of stratum, the borehole planning, observation wells planning, and so on, this information would be better described if they do sketch them. For huge scale project, both general geologic profile and divisional geologic profile are needed. Some of these drawings are cited from databases such GIS directly, but some of them as the outcome of assessment have to be drawn by investigators. Still, even the safety level, client requirements and geological conditions complexity matters the size of these drawings, there would not be plenty of files with gigabytes, a few hundred megabytes' drawings top.

## 3.3 Introduction and Comparison of extension mechanisms for building information modelling

This section mainly focuses on making an introduction of common extension mechanisms for IFC. And then the comparison is made among Linked Data, ad-hoc, XML, solely proxy extension. And in this iteration, these four extension mechanisms are introduced and discussed separately and theoretically.

### 3.3.1 Linked Data/ The Semantic Web

The Semantic Web is a Web of Data — of dates and titles and part numbers and chemical properties and any other data one might conceive of. The collection of Semantic Web technologies (RDF, OWL, SKOS, SPARQL, etc.) provides an environment where application can query that data, draw inferences using vocabularies, etc (W3C, 2015). This is introduced in 2001 with the aim of turning the current web into a "web of data", elimination unstructured and semi-structured documents (Berners-Lee, Shadbolt, & Hall, 2006). Basically, the idea behind the Semantic Web is to add semantic metadata to the existing data in order to describe data content and their relations in a way so that the meaning of the data can be processes by machines.

However, to make the Web of Data a reality, it is important to have the huge amount of data on the Web available in a standard format, reachable and manageable by Semantic Web tools. Furthermore, not only does the Semantic Web need access to data, but relationships among data should be made available, too, to create a Webof Data (as opposed to a sheer collection of datasets). This collection of interrelated datasets on the Web can also be referred to as Linked Data. Abanda et al claimed that the Semantic Web is a knowledge structure used to formally represent and share information through modelling and creation of a framework of relevant concepts and the semantic relations between the concepts (Abanda, Tah, & Keivani, 2013). The use of Semantic Web technologies represents methods of formatting data based on the meaning of the data, rather than on the structure of the data. The Semantic Web is not a separate Web but an extension of the current one, in which information is given well-defined meaning, better enabling computers and people to work in cooperation (Tim Berners-Lee, 2001). This makes the Semantic Web enable computer systems to conduct automatic reasoning, especially enable computers and more people work together even from different domains. Therefore, the Semantic Web creates possibilities for the support of large scale information sharing in the architecture, engineering, construction and facility management (AEC/FM) industry (Beetz et al, 2009). These possibilities of large scale information sharing allow the Semantic Web to offer a solution to one of the main obstacles of BIM implementation, which is the interoperability between BIM systems (Volk et al, 2014).

To achieve and create Linked Data, technologies should be available for a common format (RDF), to make either conversion or on-the-fly access to existing databases (relational, XML, HTML, etc). It is also important to be able to setup query endpoints to access that data more conveniently. W3C provides a palette of technologies (RDF, GRDDL, POWDER, RDFa, the upcoming R2RML, RIF, SPARQL) to get access to the data (W3C, 2015)**.** And OWL, RDF and SPARQL introduction are given in the following for the better understanding of the Semantic Web.

**RDF**

The Resource Description Framework (RDF) is a general framework for how to describe any Internet resource such as a Web site and its content. An RDF description (such descriptions are often referred to as metadata, or "data about data") can include the authors of the resource, date of creation or updating, the organization of the pages on a site (the sitemap), information that describes content in terms of audience or content rating, key words for search engine data collection, subject categories, and so forth. The Resource Description Framework will make it possible for everyone to share Web site and other descriptions more easily and for software developers to build products that can use the metadata to provide better search engines and directories, to act as intelligent agents, and to give Web users more control of what they're viewing. Therefore, RDF type of data storage can be regarded as a basic model of the Semantic Web (Allemang & Hendler, 2011). The RDF is an enabling technology that is recommended by the World Wide Web Consortium (W3C) (W3C, 2014). Data that is stored based on the RDF is represented by triples. These triples consist of a subject, predicate, and an object. The predicate can be regarded as the type of relation between the object and the subject. One can replace the word ‘predicate’ with ‘type of relation’. Large storages of Linked Data can be created by linking the subjects and objects semantically through these predicates. This semantically enrichment of data allows machines to automatically process and integrate available information. An example about describing Eric Miller from W3C website is given in appendix C. Here only shows the according RDF graph as Figure 8 (W3C, 2004).

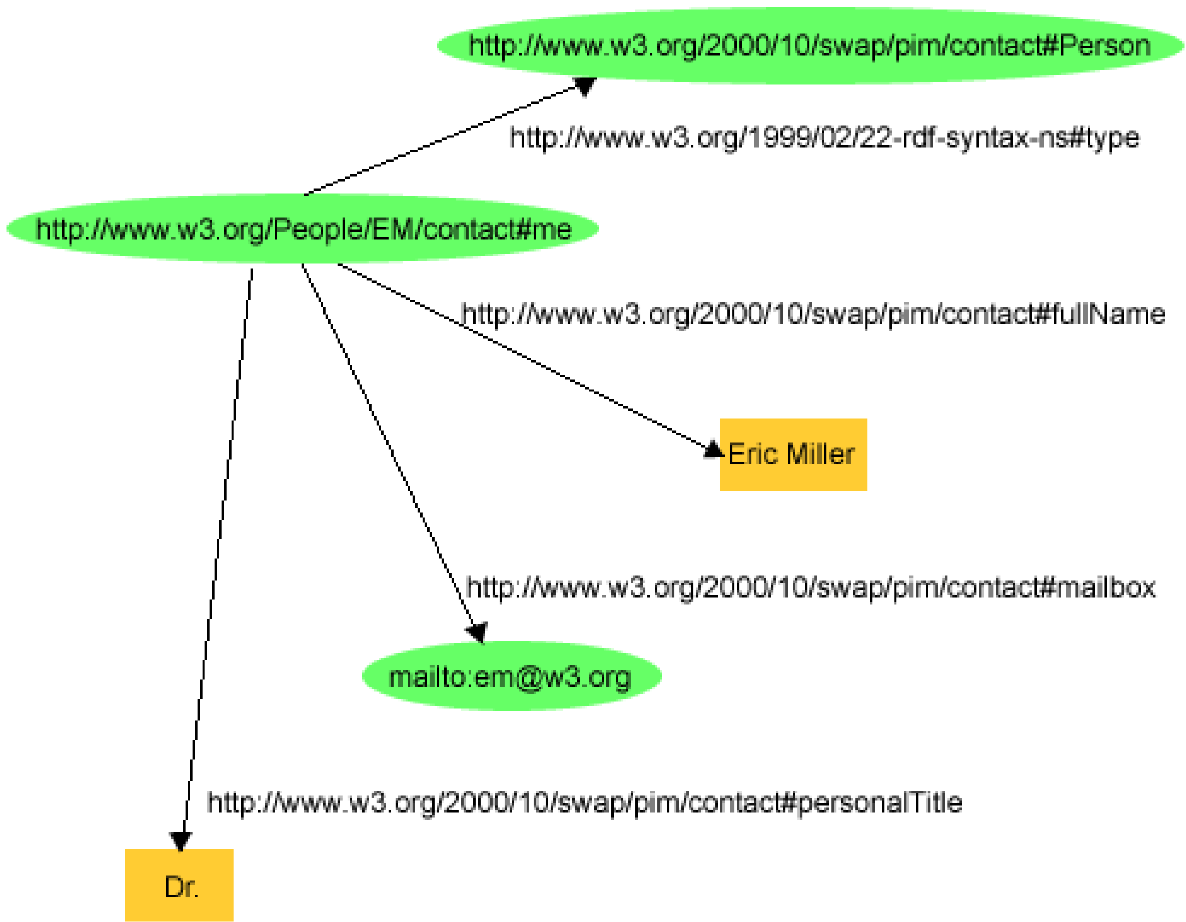


Figure 8 RDF graph describing Eric Miller (W3C, 2004)

A RDF database wherein all data is linked is therefore referred to as a graph. When merging multiple graphs the essence of the merge comes down to: "When is a node in one graph the same node as a node in another graph?" (Allemang&Hendler, 2011). This problem is solved by giving each node within a graph a Uniform Resource Identifier (URI). A URI can represent a classes, properties or individuals. This is helpful within the Semantic Web because it provides a mechanism to uniquely identify a given resource. It also specifies a uniform way to retrieve machine-readable descriptions about the resource being identified by the URI. The following figure shows the desired relationships between a resource and its representing documents (Figure 9). Since URI's have a global scope and are used consistently across contexts, the use of URI's is the main key of what gives the RDF and the Semantic Web its interoperability (Berners-Lee et al, 2006).

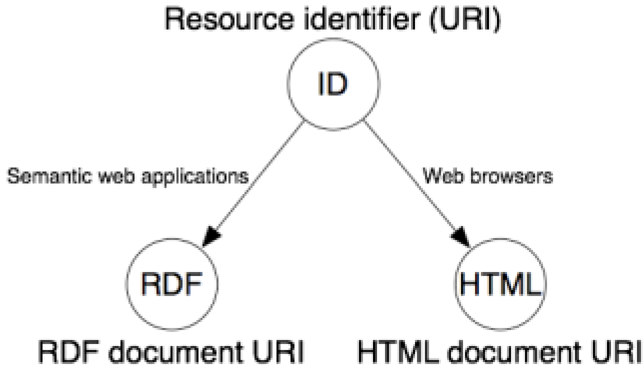


Figure 9 URI representation (Berners-Lee et al, 2006)

The Resource Description Framework Schema (RDFS) is the basic language in which the syntax is defined that is used to structure RDF based data (Yu, 2014). RDFS is an extensible knowledge representation language that can be used to create a vocabulary for describing classes, subclasses and properties of RDF resources (Brickley & Guha, 2004). This implies that the use of RDFS creates the possibility of making statements about classes of subjects and types of relationships. This also implies that RFDS allows the description of the meaning of a relationship or a class in text readable by both humans and machines. The RDFS contains the most basic elements to describe RDF based ontologies (Pieter et al, 2011). The RDFS is also a technology that is recommended by the W3C (Brickley & Guha, 2004).

**OWL**

The Web Ontology Language (OWL) is, like RDFS, an extension of the RDF. OWL is an ontology language that offers a greater expressivity in object and relation descriptions by enabling efficient representation of ontologies that are amendable to decision procedures (Berners-Lee et al, 2006). When regarding the topic 'Semantic Web', ontology formally defines a common set of domain-specific terms that are used to describe and represent a domain. Ontology defines the terms used to describe and represent an area of knowledge (Bechhofer et al, 2009).

The OWL is a language that can be used to create these ontologies. W3C formed the following definition of OWL 2: "The W3C OWL is a Semantic Web language designed to represent rich and complex knowledge about things, groups of things, and relations between things. OWL is a computational logic-based language such that knowledge expressed in OWL can be reasoned with by computer programs either to verify the consistency of that knowledge or to make implicit knowledge explicit (W3C, 2012)."

Alike the RDFS, the purpose of OWL is to define ontologies that include classes, properties, and their relationships for a specific application domain. However, when compared to the RDFS, the OWL provides the capability to express the relationships on a much more complex and richer level. This allows for the creation of ontologies with much stronger and reasoning abilities. OWL can be defined as:

OWL = RDF Schema + ‘New constructs for better expressiveness’ (Yu, 2014).
Since the OWL is standardized by the W3C in 2004, several updated versions of the standard OWL ontology have been standardized by the W3C. These were OWL 1.1 in 2005, and thereafter OWL 2.0 on October 27 2009 (W3C, 2012). These new updated versions can be considered as a subset of the previous versions (Yu, 2014). The updated versions of OWL presented an adaptation as solution for issues such as expressivity issues, problems with its syntaxes, and deficiencies in the definition of OWL species (Grau et al, 2008).

**SPARQL**

SparQL is an abbreviation of Simple Protocol and RDF Query Language (Wood et al, 2005). In 2004, the RDF Data Access Working Group (part of the Semantic Web Activity) released a first public working draft of a query language for RDF, called SPARQL (Prud'hommeaux & Seaborne, 2008). Currently (August 2006) SPARQL is a W3C Candidate Recommendation. Essentially, SPARQL is a graph-matching query language. Given a data source D, a query consists of a pattern which is matched against D, and the values obtained from this matching are processed to give the answer. The data source D to be queried can be composed of multiple sources. A SPARQL query consists of three parts. The pattern matching part, which includes several interesting features of pattern matching of graphs, like optional parts, union of patterns, nesting, filtering (or restricting) values of possible matchings, and the possibility of choosing the data source to be matched by a pattern. The solution modifiers, which once the output of the pattern has been computed (in the form of a table of values of variables), allows to modify these values applying classical operators like projection, distinct, order, limit, and offset. Finally, the output of a SPARQL query can be of different types: yes/no queries, selections of values of the variables which match the patterns, construction of new triples from these values, and descriptions of resources (Jorge Pérez et al, 2006). The query language can query process data base systems that consist of RDF triples (Prud'hommeaux & Seaborne, 2008). Since the query language can be used to query for data that is stored in RDF, it can also query for data based stored based on OWL (Birte, 2011). The query results can be result sets or RDF graphs. A SparQL query can query a set of triples like RDF triples, except that each of the subject, predicate, and object may be a variable targeted by the query (Karan & Irizarry, 2015). An example is presented in Figure 10. Figure 10 shows a SPARQL query with one filtered basic graph pattern that retrieves the names and email addresses of persons whose name start with “Tim” and email address contains “w3c”. The results are ordered by the name, the number of results is limited to five.

```
SELECT ?name ?mbox WHERE {
  ?x foaf:name ?name .
  ?x foaf:mbox ?mbox .
  FILTER regex(?name, "^Tim") && regex(?mbox, "w3c")
} ORDER BY ?name LIMIT 5
```

Figure 10 an example of a SPARQL query (Leser, 2008)

The SparQL is able to facilitate the querying of RDF graphs to get specific information, and run automated regular queries against RDF datasets to generate reports, also its interoperability with programming languages for example Python, allows the development of an application that can carry out these queries.

**3.3.2 XML**

Extensible Markup Language (XML) is a markup language that defines a set of rules for encoding documents in a format that is both human-readable and machine-readable. The W3C's XML 1.0 Specification (W3C, 2013) and several other related specifications, (Timeline, 2013)—all of them free open standards—define XML. The design goals of XML emphasize simplicity, generality, and usability across the Internet. (W3C, 2013) It is a textual data format with strong support via Unicode for different human languages. Although the design of XML focuses on documents, the language is widely used for the representation of arbitrary data structures (Fennell, 2013) such as those used in web services. Several schema systems exist to aid in the definition of XML-based languages, while programmers have developed many application programming interfaces (APIs) to aid the processing of XML data.

As of 2009, 100 document formats using XML syntax had been developed, (OASIS, 2005) including RSS, Atom, SOAP, and XHTML. XML-based formats became the default for many office-productivity tools, including Microsoft Office (Office Open XML), OpenOffice.org and LibreOffice (OpenDocument), and Apple's iWork. XML has also provided the base language for communication protocols such as XMPP, Applications for the Microsoft, NET Framework use XML files for configuration. XML has come into common use for the interchange of data over the Internet. IETF RFC 7303 gives rules for the construction of Internet Media Types for use when sending XML. It also defines the media types application/xml and text/xml, which say only that the data is in XML, and nothing about its semantics. RFC 7303 also recommends that XML-based languages be given media types ending in +xml; for example, image/svg+xml for SVG. Renaud et al presented an extension of the BIM technology that allows managing information during the entire lifecycle of an AEC project based on the standard IFC and a semantic indexation method on XML grammars. They use XML as a standard for the generation of the ad hoc data and the standard IFC for 3D numerical models (Renaud et al, 2008). Substantial efforts have been made to continuously develop the IFC object model (IAI, 2000, 1999, 1998) and to promote the IFC-based software applications to the AEC/FM industry. Especially in the architectural CAD area, commercial IFC solutions have been or are being made available to CAD users and to other software applications. An active implementation area is in the development of the IFC toolboxes as underlying IFC information supporting platforms for storage, management, and exchange, sharing of IFC product model data. William mentioned that EXPRESS and XML are two different languages for representing data. The IAI began its work several years before the appearance of XML, and the IFCs are written in EXPRESS. Since its arrival, XML has quickly become the standard method for exchanging data over the Web, with extensive supporting standards and software infrastructure. ISO/STEP has a mechanism for transferring EXPRESS files, and such files can be transferred over the Web. The problem with such files is that they can be interpreted only by software designed for the EXPRESS format. To software designed for XML, these files would be unintelligible. The ability to make use of all the software based upon XML depends upon the ability to translate between EXPRESS and XML. The problem with such translation is that the two languages are very different -- each has concepts that are not present in the other -- so simple mappings are precluded. ISO/STEP Part 28 is a mechanism for representing EXPRESS in XML without loss of information.

However, the XML representation of data by this method is very different from the way data is typically represented in XML. Part 28 files can be manipulated using XML technology, but they can still be interpreted only by software expressly designed for them. Part 28 files also suffer from being many times greater in size than would be the case for the same data as typically represented in XML. The BLIS Project and the IAI have developed XML representations of the IFCs. The BLIS Project first developed BLIS-XML. The IAI then developed the very similar ifcXML (IAI, 2001b). ifcXML illustrates the difficulty of representing EXPRESS in XML (Behrman, 2002). The EDM package (EDMTechnology, 2002) provides full set of APIs for processing IFC and XML objects with Web support. Yang modelled a property database to store also manage the pre-defined and new-created property and Pset definitions in the XML format for ADT. Instead of using tabular forms to hold these definitions in the database, XML files are employed to maximize the information structuring flexibility, property definition accessibility, and property information exchangeability across applications. The property database is composed of XML documents. Each XML file defines one Pset with a collection of properties (Yang, 2003). The information structure of each XML document is described in DTD (Ahmed K., 2001). Zhang suggested that IFC is an ideal standard for transferring data between different software platforms. The native IFC format is based on plain text, and will become quite large if used to store all the building information in one file. And since IFC also supports XML format storage. It allows any IFC model to be described in ifcXML format under the XML schema. He proposed paper proposes an ontology built with Web Ontology Language (OWL) based on IFC specifications to help in the information retrieval process from an IFC model. With simple reasoning build in the ontology, an information retrieval system could directly query the IFC model in XML format (Le Zhang, 2011). aecXML (IAI-Na, 1999) is a domain of the North American Chapter of the IAI. It started at Bentley in 1999 with the objective of developing within one year XML schemas for the AEC industry (A schema is a representation of data). LandXML (LnadXMLorg, 2016) is an effort to standardize civil engineering and survey data for land development. Such development is typically designed with CAD software, and a trend in this software has been to extend the data representation from simply a set of lines to include the meaning of the lines. The goal of LandXML is to provide a medium for the exchange of land development data among the various software applications of the AEC project team and for official submission to owners. Green Building XML (gbXML) (gbXMLorg, 2016) is a schema developed by the small engineering consulting firm GeoPraxis for data used in energy analysis software. Sophisticated software packages, such as DOE-2 and EnergyPlus developed by the US Department of Energy, can accurately predict the energy characteristics of a building from its design, but the difficulty of entering the necessary data into such packages has been a significant obstacle to their use. The desire to get such data automatically from CAD software led to one of the BLIS use cases that we saw above and is also the motivation for gbXML. Behrman also suggested that the data interchange standardization needs of the AEC industry are not well served by the IAI. Moreover, data interchange standards for use over the Web should be developed in XML. The Web is clearly an extremely important medium for exchanging data, and not just from computer to human, but also from computer to computer. It is governed by a set of standards, including HTTP and HTML, developed by the World Wide Web Consortium (W3C). The W3C standard for exchanging data over the Web is XML, which has been widely adopted and has an extensive and rapidly growing base of supporting standards and software infrastructure. To take advantage of this base of supporting standards and software infrastructure, data interchange standards need to be in XML. Data interchange standardization efforts should make use of existing, widely adopted, cross-industry XML standards wherever possible. The data interchange standardization needs of the AEC industry would be better served by independent minimalist standardization efforts. The fragmented AEC industry lacks the high-level commitment of a critical mass of key players along with the substantial resources necessary for a large-scale standardization effort such as RosettaNet, but data interchange standardization in this industry can be advanced through independent minimalist efforts such as LandXML. When the AEC industry reaches the point of having multiple XML standardization projects, such an architecture would be helpful. Since the AEC industry is lagging other industries in its development of XML data interchange standards, by the time it reaches this point, it should be able to draw upon the experience of analogous architectures from other industries (Behrman, 2002). Sang-Ho Lee et al provide a method for the integration of a 3D bridge model and document fragments. Since the document contents can change as the corresponding engineering process changes, this study adopts a loosely coupling concept for supporting independence of each information set rather than proposing a specific data model in integration. As a core technique for the integration, this study used an enhanced document analysis technique. The technique provides a generic method extracting document hierarchy and generating XML-based semi-structured document information (Sang-Ho Lee, 2013). Stouffs et al extended missing required IFC objects or properties via ifcXML files in the process pf extending IFC for parametric sustainable building design, and use Solibri Model Checker as a model checking tool checking the operability and consistence of the model in the custom schemata (Stanimira et al, 2013).

### 3.3.3 Proxy extension

IFC schema extensions are long-term developments that depend on the IFC release cycles and have to be discussed with the Model Support Group of the IAI. It typically requires two or more years to integrate proposed extensions in a new IFC release, which then would enable to start the implementation. This time frame does not really fit to research projects which have to start prototype developments within one or two years. Therefore, if possible the strategy of such projects is to avoid schema extensions, which means to use property sets, proxy elements and references to external data structures. Property sets and proxy elements enable to extend the scope of IFC without changing the schema, but require additional implementation agreements about the meaning of properties and proxies if they shall be shared with other CAD software. A single property is key-value pair that can be attached to nearly any kind of elements and thus enables to extend their attributes. A proxy element is an object that inherits main functionality from its super type like for instance a building element, but without having a predefined meaning. The meaning or class type is described by the name attribute, which enables to introduce new element types. The dynamic extension mechanism comes with the risk that the IFC standard evolves into different dialects that are only agreed between few partners and finally results in incompatible IFC files. As naming of properties and proxies typically depends on the context and language in which they are used there are always naming conflicts that are often leading to unusual definitions. However, the naming problem has changed in IFC2x4, which supports multilingual property sets and links to dictionaries that for instance can be based on the International Framework for Dictionaries (IFD, ISO 12006). Such 'mapping tables' would help to make name-based extensions more understandable as they can be provided in different languages (Weise et al, 2009).

The IfcProxy is intended to be a kind of a container for wrapping objects which are defined by associated properties, which may or may not have a geometric representation and placement in space. A proxy may have a semantic meaning, defined by the Name property, and property definitions, attached through the property assignment relationship, which definition may be outside of the definitions given by the current release of IFC. The ProxyType may give an indication to which high level semantic breakdown of object the semantic definition of the proxy relates to. The Tag property may be used to assign a human or system interpretable identifier (such as a serial number or bar code) (IfcProxy, 2016). It is in the core layer, an entity type can be instantiated, not to a specific object. And it inheritance graph is shown in Figure 11. Researchers could set ProxyType and Tg by instantiating IfcProxy, and describe the self-defined object with PropertyType and optional geometry information. Within it, ProxyType is IfcObjectTypeEnum data, which can be defined as geometry, process, control, resource, manpower, item and tec., Tag is used to describe self-defined property.

When using IfcProxy extension mechanism, it is possible to appear "repeat" IfcProxy object description, but after adopting IfcProxy property information judgement, users would be able to identify different type of self-defined object. With this extension mechanism, it could be compatible to existing IFC tools, and relatively small changes to the IFC model frame, but low running efficiency (Zhang, 2009).

Steel et al gave a brief situation and example to use the proxy extension, they mentioned for cases where the IFC does not provide a particular modelling construct, the language includes a mechanism for the modelling of IfcProxy objects, which serves as a kind of extension mechanism. For example, in the case of landscaping, there is no IFC construct for trees or shrubs, so these are often included (with geometries) as IfcProxy objects (Steel et al, 2012). Ma (Ma Zhiliang, 2011) established an information requirement model for construction cost estimating for tendering in China, which includes sevven aspects of information entities. Each aspect of the information was expressed by using the IFC standard to verify the completeness of the IFC standard and to establish the IFC-based information model.

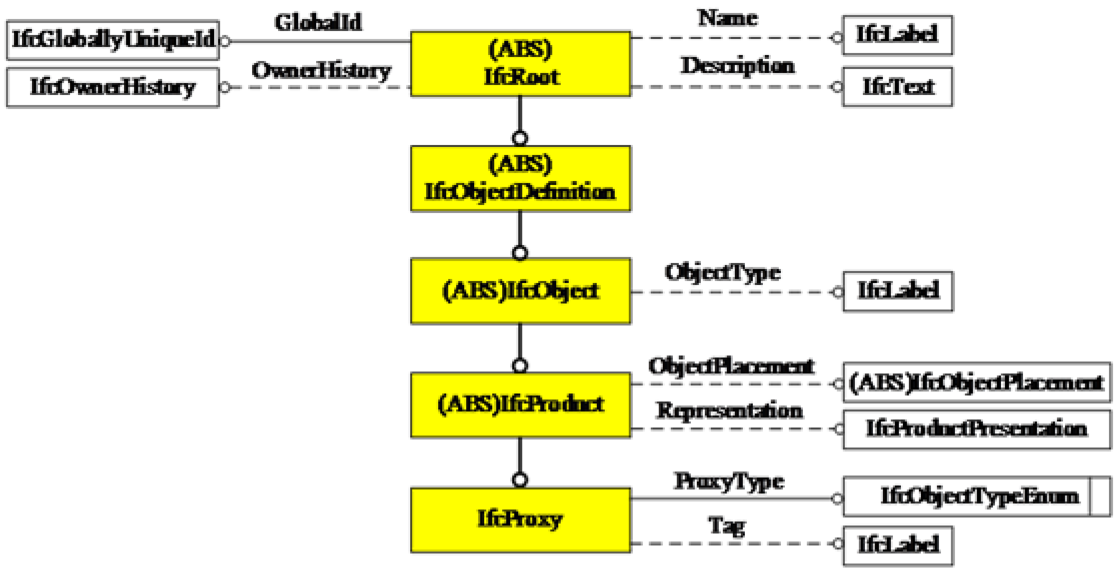


Figure 11 IfcProxyinheritance (buildingSMART, Ifcproxy, 2016)

And extend the IFC standard with the proxy elements and property so that could be applied to the development of a construction cost estimating software. Jubierre and Borrmann' proposed extension introduces the integration of the concept of multiple levels-of-detail into the IFC standard. For the first level of extension they use the standard IFC4 schema without any tunnel-specific extensions.

Accordingly, we use the spatial structure entities Building and BuidingStorey to model the Tunnel and TunnelPart objects. The tunnel spaces (IfcFullTunnelSpace, IfcLiningSpace, etc.) as well as the physical objects (IfcTunnelElement) are modeled by IfcProxy objects. As the schema employed on the Level 1 is the standard IFC4 schema, any IFC viewer capable to read IFC4 files is able to display the model correctly. However, the tunnel-specific semantic information can only be represented in a much-reduced manner, as proxy objects are applied (Jubierre & Borrmann, 2014). Motamedi et al add the definitions for RFID components to the BIM standard and to map the data to be stored in RFID memory by using proxy elements and property sets or types due to the practicality to meet specific local requirements and also the new defined entities need at least two years to prove from BSA (Motamedi et al, 2016). Stascheit et al present an IFC-based product model for mechanized tunneling that is used to automatically create a complex numerical simulation model. A model mapping procedure is proposed that links IFC representations of the ground, the tunnel, and the shield machine with the corresponding input of the parametric simulation model. To cover all required information in mechanized tunneling, the holistic IFC product model—the ground data model (GDM) is developed. Due to the missing extensions of the IFC regarding ground data, objects of the GDM are represented as IFC proxies. A proxy class is a generic container defined by its associated geometric and semantic properties (BuildingSMART 2011). For example, if a ground layer should be stored, a new proxy element is added to the partial ground model. The proxy has attached both a geometric representation defining the region of the layer and semantic information on the material properties by means of so-called property sets (Stascheit et al, 2016). See at al mentioned that the internal data model, named the Simulations Model or SimModel, is based on IFC, which is the international standard for exchange of BIM data. However, it also includes substantial extensions in the HVAC domain to support the variety and level of detail of the component models in EnergyPlus. When exporting to IFC, these extensions are currently modeled using the standard IFC extension mechanisms (Proxy objects and PropertySets). Their research indeed argued that Proxy extension mechanism is a highly-recommended approach in HVAC domain (See et al, 2011). On the other side, the German researchers conducted more work on IFC-based product modeling for tunnel boring machines which are additional engineering fields. They focus on Earth Pressure Balance (EPB) shield machines, which are frequently used for tunneling in unstable ground conditions. EPB shield machines consist of several machine components such as the cutting wheel, the excavation chamber, screw conveyors and others. Since the current IFC notation does not provide classes to capture these elements, one possibility would be to represent these elements by so called proxy classes. A proxy class can be understood as a container defined by associated properties (BuildingSMART 2011). Furthermore, a geometric representation can be assigned to it. Therefore, proxy classes can be used as substitutes for each element which is not captured by the IFC notation. Indeed, this could be an appropriate solution if only few undefined elements exist, but to represent a TBM many elements must be modeled (Hegemann et al, 2012). Afterwards, a great concept has been officially proposed by Vilgertshofer et al, they proposed the general concept for a space oriented approach to describe shield tunnel models by extending the IFC and the integration of multiple levels of detail into the IFC standard in the scope of considering downward compatibility aspects. The proposal therefore introduces three consecutive levels of extension. Thus, we enable any IFC-viewer supporting IFC4 to visualize the exemplary instance files created in the first level by using proxy objects (Vilgertshofer et al, 2013).

**3.3.4 'Ad hoc heterogeneous data'-Barbi/LexiCon**

At the end of 2006, Howard&Bjork conducted a qualitative study based on information from a number of international experts and has asked a series of questions about the feasibility of BIMs, the conditions necessary for success, and the role of standards with particular reference to the IFCs. As the analysis of the responses, they mentioned When Alvar Aalto, the famous Finnish architect, was asked about dimensional standards he said that his office module was 'about a millimeter or less'. Predictably the respondents to this question all believed in standards but differed as to what should be standardised, how formal standards should be and whether they were likely to be observed. The ability to transfer information digitally throughout the building process has emphasised the need for standards. For wide recognition, it was felt that they should be formalised internationally by ISO, but that de facto standards which were widely used should be capa-ble of formalisation. The European approach was said to be irrelevant to the US where the industry is more disor-ganised and only procurement standards have any legal status. Diverse and changing project teams depend upon standards. Common libraries should be usable by different BIMs. Proprietary standards are suspect and de facto ones, while faster to produce, often leave out essential elements. Standards should not be a barrier to creativity and innovation. They may apply to: language, products, elements or processes. Those relevant to construction mentioned include: IFC, IFL ISO 12006-3 (Barbi/Lexicon), IDM, CIS/2 steelwork, GML city mod-els, UN/CEFACT business, Process Protocol, Uniclass and Avanti (Howard & Bjork, 2007). With IDM and MVD concepts to extend the scope of standardization of IFC-based exchanges beyond the IFC information model, the International Framework for Dictionaries (IFD) effort was formally initiated within buildingSMART International around this same timeframe, in April 2008 (ifd-library.org). Referred to as the third pillar of IFC data exchange, together with IDM and MVD, IFD describes what is exchanged by providing a mechanism that allows the creation of dictionaries or ontologies, to connect information from existing databases to IFC information models (Bell & Bjørkhaug, 2006). Initial work on a standard to fulfill similar purposes were initiated in 2006 as collaboration effort between the BARBi project in Norway and the Lexikon project in the Netherlands, which work was then continued within buildingSMART International (ifd-library.org). IFD – International Framework for Dictionaries specifies WHAT the exchanged information means. IFD is another ISO standard (ISO 12006-3:2007), whose development started in 1999, and is used to add semantic to part of the information present in a BIM model so that it can be understood and processed regardless of language and nationality. As stated before, the semantics represented in IFC are limited. For example, IFC can record that a certain object is a Window and that it is made of a material (registered in its "Material" property). But the Material property can hold only (any) text string. It could be 'wood', 'PVC', 'aluminum' or even 'sugar'. Its content holds no semantic, as far as IFC is concerned. This is where IFD enters. The implementations of IFD are able not only to describe (to humans) what a material is, but also to offer its translation to different languages, working as a multilanguage dictionary. It can also describe its relationships with other concepts, acting as taxonomy. In IFD, each name is associated with a global unique identifier (GUID), allowing the computer to understand its meaning and to be able to perform searches on product catalogues, briefing documents, specifications, matches in bid results, etc. Several efforts for creating implementations of IFD are in place now (Norway's BARBi Library, Netherland's LexiCon, France's EDIBATECH and IAI's IFD Library). Those efforts will allow the computer to fully understand a building information model, helping on many tasks of its users. But those benefits will be only available in countries that have developed an implementation of IFD (or cooperated on international efforts like the IFD Library), because of its very regional character (Santos, 2009). There are indeed more description about the BARBi, LexiCon and some related research work are presented followingly.

**BARBi**

BARBI is a project initiated by the Norwegian construction industry to establish a reference data library with a complete collection of all concepts and objects from the building and construction industry with associated properties and relationships. The library will contain everything from complete constructions down to individual parts or products. Resources, activities and references to standards, classification tables and application protocols like Ifc (International Alliance for Interoperability, Industry Foundation Classes) and STEP-APs (Standard for The Exchange of Product model data, Application Protocol) will be included in the library. The Norwegian Building Research Institute has a central role in the development of the library and is working in close cooperation with Norwegian and international organizations involved with similar projects. The work is coordinated internationally from the Norwegian Council for Building Standardization.

Through several Norwegian and international projects there is a growing understanding that existing standards and classification systems do not cover the current and future needs for structuring information. A paper-based system works well for manual information handling but fails when used in computers. The systems are not accurate enough for computerizing and covers only limited aspects related to buildings or objects. The idea of the “ultimate classification system” also becomes utopia with rapidly increasing demands for information, constantly changing products, techniques and technical solutions. Existing classification-systems are despite of this widely used both as standards for information exchange and for information handling in general.

The BARBi project was initiated after the conclusion of another Norwegian SiB (Samspillet i Byggeprosessen “Interaction and cooperation in the building process”) project called “Further development and revision of tables for structuring of information” in February 1997. The intention of this project was to determine the need for revision on existing tables. The report however concluded that there were several problems connected to the use of classification tables, and that there was a need for a deeper study of alternative ways of handling information. The BARBi project was initiated January 1998. The project has been divided into several sub-projects of which the most important are

| | |
|---|---|
| January 1998 - August 1998: | A study of the state of the art on the field with an evaluation of the leading initiatives. |
| September 1998 - January 1999: | A test of Version Snapshot-E of the EPISTLE model. Modelling a wall into the POSC/CAESAR data reference library. The “Wall test case” [P/C] |
| February 1999 - May 1999: | Evaluation of other models based upon the experience from the “Wall Test case” and POSC/CAESAR |
| May 1999 - October 1999: | Development of a subset of the EPISTLE v3.1 framework for use in the building industry. Assessment of the Dutch BAS (Vereniging Bouw Afsprakenstelsel) initiative LexiCon versus the EPISTLE v3.1 subset. |
| November 1999 – October 2000: | Contribution to the development of the ISO/PAS 12006-3 framework [ISO/PAS]. Study of IAI Ifc 2.x in connection to BARBi. |
| November 2000 – January 2001. | Population of BARBi using the ISO/PAS 12006-3 framework. Development of tools to convert EPISTLE data to BARBi data using EXPRESS databases and the EPM data manager. Development of a web-application and a handbook for the use of the ISO/PAS framework (BARBi,2009). |

Bjorkhaug’s research referred BARBi project tests the integration of IFC and ISO 12006-3 reference data by mapping the IFC to the content of the BARBi library. This provides a link between the generic national object names and definitions, and the IFC objects and properties. This allows not only for automatic translation of objects between national standards and IFC but also for exchange of reference data in IFC format. The result of the mapping will hopefully begin a standardization of all exchanged data. Also they proposed using building models and reference data for benefit building and construction projects by integrating ISO 12006-3 and IFC, which shows in Figure 12.

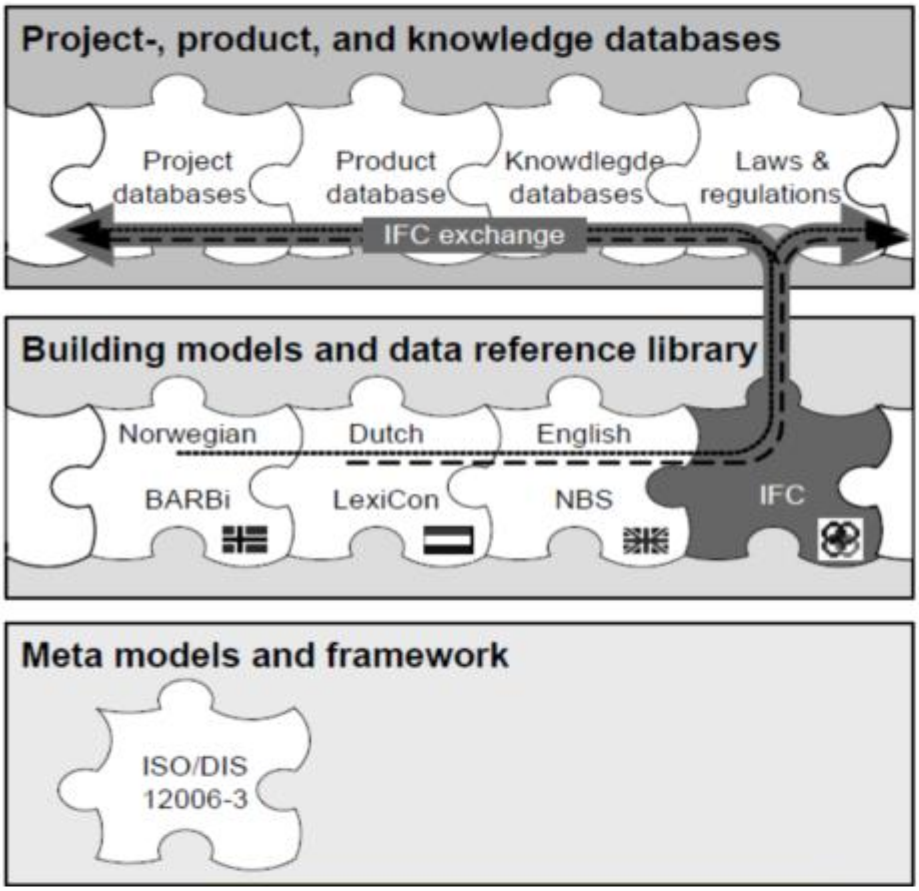


Figure 12 'integration of ISO 12006-3 and IFC' (Bjørkhaug, 2003)

Figure 12 shows the three different layers of abstraction of information. The bottom layer is the core framework with basic concepts like subjects, activities, actors, units, and properties. The middle layer includes generic reference data libraries and building product models like IFC, while the top layer consists of instances of objects like a product in a product catalogue, a door in a building, or a "best practise" in a knowledge database (Bjørkhaug, 2003).

**LexiCon**

The LexiCon has been presented at several international conferences (the ECPPM '98 conference in Watford, UK, CEC 99, Espoo, Finland, August 1999, and INCITE 2000, Hong Kong, January 2000). It has also been discussed within the International Construction Information Society (ICIS), within the International Alliance of Interoperability (IAI) and, as mentioned above, within ISO TC59/SC13 and ISO TC184/SC4. A description of its structure

can be found in (Woestenenk, 1999). Following is a brief description of its structure and contents.
The LexiCon describes so called Built Objects, using standardized attributes. Built Objects are concepts relevant to the construction industry. These concepts are known to the industry by their names; the problem is, however, that these names are interpreted differently by different people and in different circumstances. What the LexiCon tries to do is to provide an unambiguous description of a named concept through a set of attributes. Attributes should be computer interpretable. Defining the concepts this way makes these concepts independent of their names, thus allowing for synonyms and homonyms, as well as language independency. In earlier publications, the following EXPRESS-G model (see Figure 13.) was shown describing the model on which the LexiCon is based.

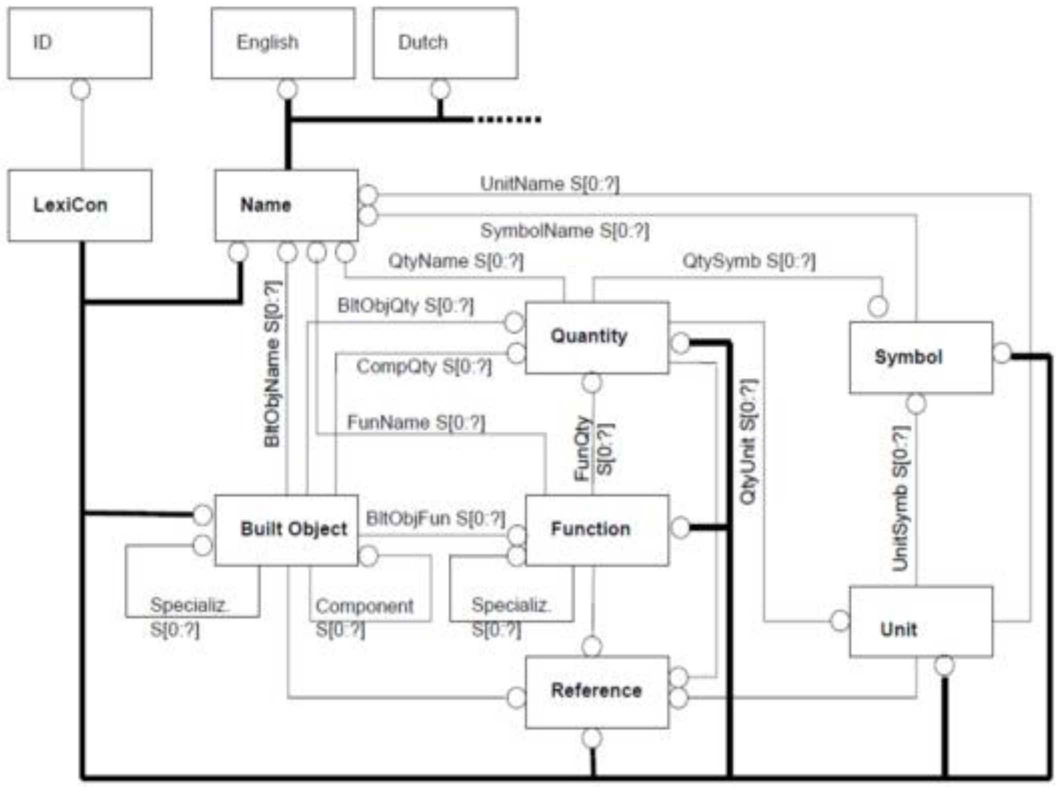


Figure 13 Lexicon model (Woestenenk, 1999)
A new version of the model will follow the recommendations of ISO TC59/SC13/WG6, the working group responsible for the development of the structure of an object-oriented classification framework.

With a not yet fixed structure a tool has been developed by STABU to populate the LexiCon. This tool is a Windows desktop application, showing the concepts as classes in a specialization hierarchy and the description of each class in an adjacent pane (see Figure 14.).

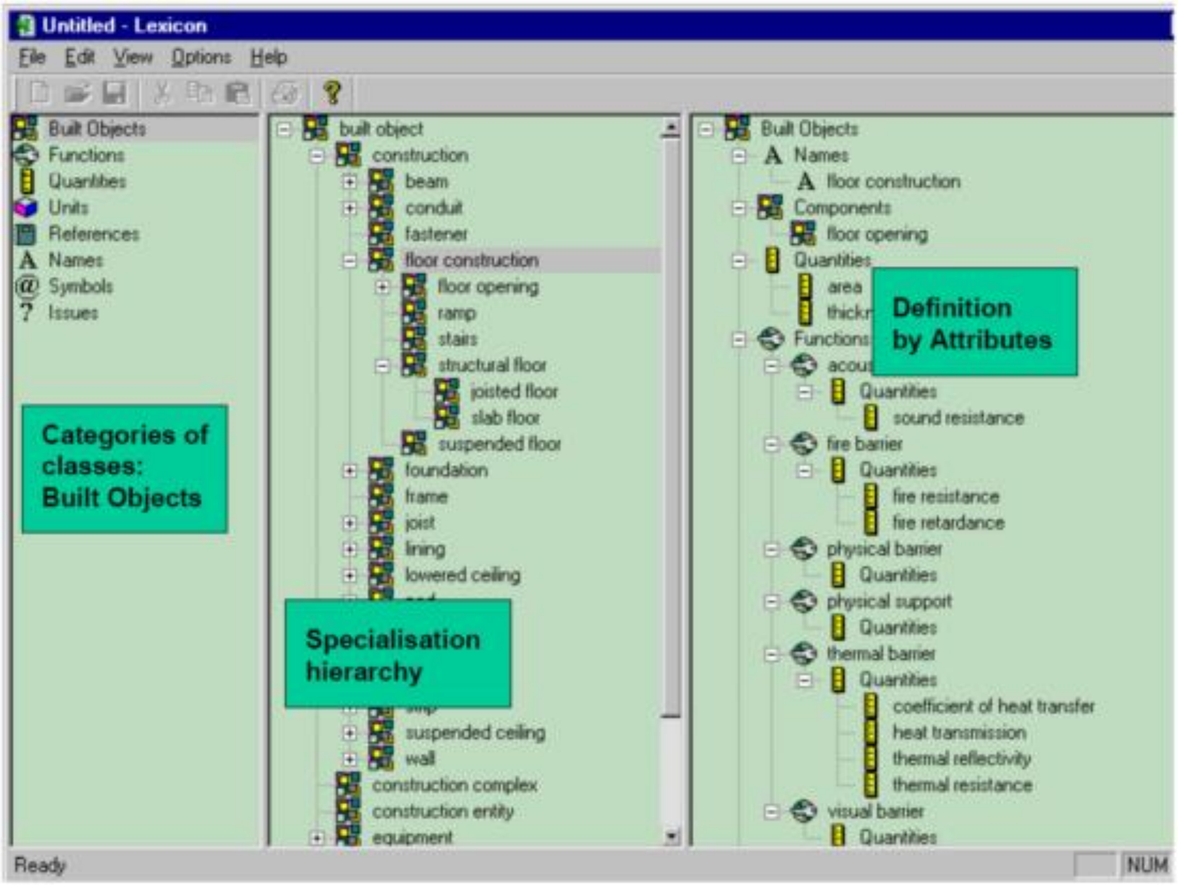


Figure 14 The LexiCon tool (Woestenenk, 1999)

Ultimately, a Web-based tool will be developed to allow for publishing the LexiCon on the internet. A preliminary version of such a tool has been developed by TNO Building and Construction Research (BOUW), The Netherlands.

In Harrison & Donn's research (Harrison&Donn, 2006), they clearly mentioned that there has been considerable research into how AEC data and knowledge can be digitally described, recorded and exchanged. Two notable efforts have been Industry Foundation Classes (IFC) and the LexiCon semantic system for the built environment. IFC's are a structured, extensible model for digital AEC information (M. Weise, 2009). Unfortunately, even after ten years of development IFC's are still not comprehensive enough to satisfy all use cases, a factor in their limited adoption within the industry. The LexiCon is not a data model but rather an effort to create a database of construction concepts (Woestenenk, 2002). The LexiCon can provide a language neutral way of describing construction information. Both technologies if successfully implemented could infuse vast quantities of meta-data into digital AEC content. Unfortunately, due to implementation issues and standard complexities neither have gained widespread industry acceptance or support within the AEC software market.

### 3.3.5 Comparison of introduced extension mechanism

This part will discuss aforementioned four extension mechanisms separately; the strength and weakness will be studied regarding their application for IFC extension in the geological survey of tunnel from the perspective of ease of implementation, ease of use, expressivity and performance.

Ad hoc extension: there are certain researches indeed indicated the advancement and shortcoming of this extension mechanism. Beetz et al clearly point out that alternative to EXPRESS schema-based extension procedures; a number of strategies can be identied to capture domain-and organization-specific information on the four indicated levels in interoperable ways. A common practice to date is to use properties that are associated to individual objects in the IFC instance model in an ad-hoc fashion. This practice however has the shortcoming that their semantics are limited to human-interpretable forms such as string identifiers and no standardized mechanisms exist that allow the sharing and reuse of such property sets among the different and changing stakeholders in projects (Beetz et al, 2014). Also he presented that most of the content found in the bSDD has been added and edited in a semi-structured manner. Main contributions have been received from individual and national initiatives such as BARBi (Norway), Lexicon (The Netherlands), Omniclass (US), IFC4 PSets (buildingSMART International) and have been translated, merged and mapped in 'ad hoc' processes and episodic efforts. This was enabled by the close formal and informal collaboration of the individual initiatives and driven by enthusiastic and passionate stakeholders. However, such ad-hoc management is limited with regards to its scalability and sustainability: As more and more stakeholders wish to model their own domain, national classification systems and organizational structures, a number of issues will have to be addressed allow such growth. These include the prevention of 'pollution' of the library by duplicate concepts and their relations as well as avoiding and managing contradictions and inconsistencies between different items in the vocabulary. Other principal issues affect the necessity of a quality assurance mechanism including consistency and integrity checking as well as versioning control including the archival of past versions that will have to remain valid. Issues on lower technical levels such as transaction safety including roll-back capabilities are depending on the underlying implementation of such vocabulary systems that are likely to be resolved on lower technical levels. Also, Harrison & Donn's research stated due to implementation issues and standard complexities neither have gained widespread industry acceptance or support within the AEC software market (Harrison&Donn, 2006), which implied achieving this mechanism is difficult. However, for creating implementations of IFD, Norway's BARBi Library, Netherland's LexiCon, France's EDIBATECH and IAI's IFD Library are made. Those will allow the computer to fully understand a building information model, helping on many tasks of its users. But those benefits will be only available in countries that have developed an implementation of IFD (or cooperated on international efforts like the IFD Library), because of its very regional character (Santos, 2009).

Proxy extension: Weise et al (Weise et al, 2009) pointed out that proxy extension is relatively quick to implement and able to extend the scope of IFC without changing the schema, but require additional implementation agreements about the meaning of properties and proxies if they shall be shared with other CAD software. A single property is key-value pair that can be attached to nearly any kind of elements and thus enables to extend their attributes. A proxy element is an object that inherits main functionality from its super type like for instance a building element, but without having a predefined meaning. The meaning or class type is described by the name attribute, which enables to introduce new element types. And the dynamic extension mechanism comes with the risk that the IFC standard evolved into different dialects that are only agreed between few partners and finally results in incompatible IFC files. Another shortcoming is that implementation of the proxy mechanism within tools also needs to make it as easy for a user to add a new proxy object as it is to use a semantically misleading construct that presents the same visual appearance (Steel et al, 2012). Hegemann et al adopted proxy extension to extend IFC-based product model for tunnel boring machines since there are strong connections between tunneling machine types and ground conditions, and proxy classes could capture those elements, furthermore, a geometric representation can be assigned to it. However, they also claimed that a huge number of proxy classes could lead to conflicts regarding element identification, since different team members could use different names for identical or similar elements. Additionally, individual aspects of a tunneling project, for example. the ground, the tunnel or the TBM should be integratable into one IFC file. If each element of each aspect is represented by separate proxy class this can lead to great confusion (Hegemann et al, 2012). Delgado et al offered more conclusive comment that using proxy and user-defined elements are not definitive and robust solutions, which could lead to errors, ambiguities, and hinder the benefits of using the BIM approach during the operational phase of built assets (Delgado et al, 2016).

XML: XML became a W3C Recommendation as early as in February 1998 due to its genuine advancement: 1. It simplifies data sharing 2. It simplifies data transport 3. It simplifies platform changes 4. It simplifies data availability. Many computer systems contain data in incompatible formats. Exchanging data between incompatible systems (or upgraded systems) is a time-consuming task for web developers. Large amounts of data must be converted, and incompatible data is often lost. XML stores data in plain text format. This provides a software- and hardware-independent way of storing, transporting, and sharing data. XML also makes it easier to expand or upgrade to new operating systems, new applications, or new browsers, without losing data. With XML, data can be available to all kinds of "reading machines" like people, computers, voice machines, news feeds, etc (w3schools, 2016). Behrman (Behrman, 2002) recommended that 'Data interchange standardization efforts should make use of existing, widely adopted, cross-industry XML standards wherever possible' because it XML could simplify implementations within the development process unlike structuralist approach make implementing a large, complex standard such as IFC difficult. Also, representing EXPRESS in XML can be no information loss. Even the xml extension mechanism has massive and clear advantages, still, there are certain shortcoming raised by its natural characteristics.1. Xml data types cannot be compared or sorted. 2. Cannot be used as a parameter to any scalar, built-in functions other than ISNULL, COALESCE, and DATALENGTH. 3. Cannot be used as a key column in an index. These implies that the extended data model fail to be reused even it can be transferred through hardware and software easily. Also, in some cases, the data could be hard to completely understood even they are completely expressed. It is hard to tag the xml data, as a consequence, inheritance would be harsh to express in the elements relationships. Moreover, xml file huge size used to be an issue, especially involved huge projects.

Linked Data: The ‘Anyone can say Anything about Anything’ (AAA) principle is of the fundamental notions of the Semantic Web and Linked Data efforts. The state-ment not only documents the idea of a democratic, non-centralized and independent approach to defining meaning, opinions and definitions of a particular Universe of Discourse (UoD). “Can say” also means that the requirements of the underlying technologies should allow anyone to share and expose their views with as a low a threshold as possible that can be used and interpreted with as little effort as possible. A minimal set of agreements that have been formulated as the ‘five star’ requirements for data (http://5stardata.info/) allow sharing and consuming such structured data in more interoperable ways than provided by the so-called ‘information silos’ – pro-prietary databases with thick layers of non-standard interfaces – that are currently predominant on the web and in service base architectures. At its structural layers of the Semantic Web technology stack, the Resource Description Framework (RDF) allows the creation, reference, and extension of data sets across the boundaries of network nodes. A further essential enabler is the formulation of a universal exploitation-mechanism and query language that is intended to work independent of underlying data base schemas and implementation specifics. The Simple Protocol and RDF Query Language (SPARQL) provides a mechanism to expose such data sets and vocabularies in straight-forward and affordable ways as so-called ‘SPARQL endpoints’ (Beetz et al, 2014). Though, there are some limitations with the RDF, when particularly considering the topic of interoperability, challenges reside mainly in the creation and management of the links between diverse information models in RDF (Pauwels, 2014). Gutierrez et al. discuss the basic issues of the semantics and complexity of a conjunctive query language for RDF with basic patterns which underlie the basic evaluation approach of SPARQL (Gutierrez et al, 2004). Haase et al (Haase, Broekstra, & Volz., 2004) present a comparison of functionalities of pre-SPARQL query languages, many of which served as inspiration for the constructs of SPARQL. Nevertheless, there is no formal semantics involved.

# 4. Research Model

To extend the shield tunnel BIM model with comprehensive geological data in the proper way, the IFC shield tunnel is extended first after studied on the existing Ifc-ShieldTunnel. And then regarding the extension mechanisms' theoretical comparison, the detailed comparison in the case of geological data extension within shield tunnel BIM model is discussed systematically. In the end, developed the Linked Data approach that can be applied to extend shield tunnel BIM model.

## 4.1 IFC shield tunnel extension

As aforementioned the most contained information in the IFC-ShieldTunnel and intended extension within it are shown in Table 4.

Table 4 comparison between existing IFC-ShieldTunnel and intended extension

| domian | IFC-ShieldTunnel | Intended extension model |
|---|---|---|
| Geological | Mainly stratum information, ground water information | Not only stratum information and groundwater information, but also geological in situ test and laboratory test information |

According to IFC layer structure, domain layer as the highest layer defines different domain/field specific information. The current IFC 4 defined eight domains, which are building controls, plumbing fire protection, structural element, structural analysis, HVAC, electrical, architecture and construction. And the shield tunnel information model would focus on the extension of geology domain as Figure 15 shown. This chapter contains most IFC entity extension and property set extension.

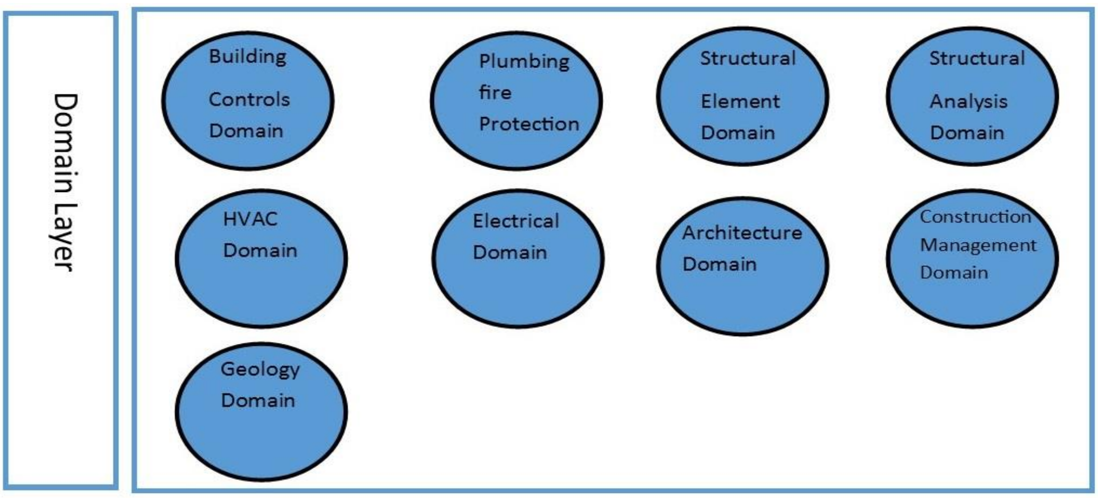


Figure 15 IFC domain layer extensions

Meanwhile, the newest IFC 4 standard has not given the shield tunnel related entityies, the only corresponding entity is the new added IfcCivilElement (Figure 16). Abstract entity IfcCivilElement is used to describe elements evolved in infrastructure, such as road, bridge, tunnel and etc. this is the core entity of researching information model, which is geological survey model.

Geological survey information model mainly includes borehole information, in-situ test information, laboratory test information, stratum information and etc. Among them, drilling hole can be seen as a physical element which has certain spatial morphology, stratigraphic distribution information, sampling information and so on within drilling hole are the different attributes of the physical element. Drilling hole information would be able to connect with some in situ test information, drilling hole sampling information could connect with laboratory test information.it should be pointed out that, entities and property sets of geological survey information model are in the geology domain.

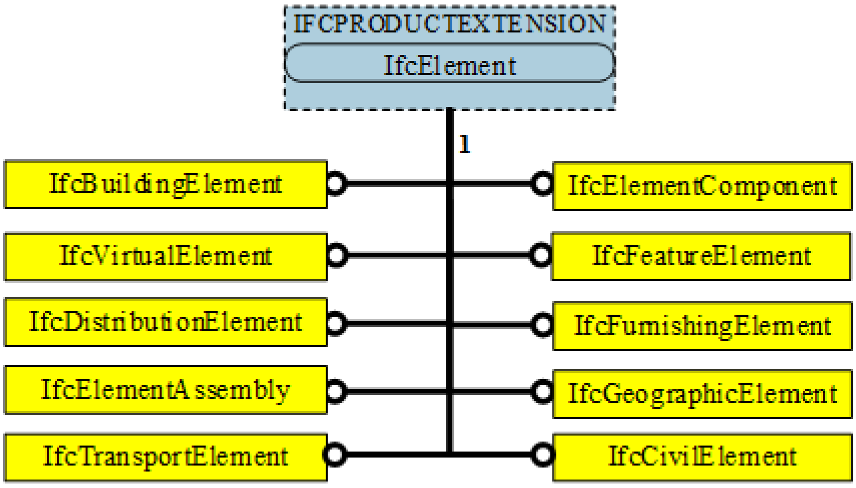


Figure 16 IfcElement inheritance (buildingSMART, IfcProductExtension, 2016)

### 4.1.1 Physical Element

This part proposed developing IfcCivilGeologyElement abstract entity under IfcCivilElement entity to describe geology element information specifically. The entity further derived stratum information, borehole information, water observation good information and geology sample information as IfcStratum, IfcBorehole, IfcWaterObservationWell, IfcGeologySample respectively, as shown in Figure 17. And IfcGeologySample derived IfcSoilSpecimen to describe the test sample from the borehole. The detailed information of these entities uses IfcPropertySet extension to describe, and build the relations with corresponding objects through IfcRelDefineByProperties.

Referring to geology information requirements analysis aforementioned in the last chapter, for borehole information description, property set extension can be adopted, named Pset_BoreholeCommon, for further information please refer to Appendix B.

For water observation well entity IfcWaterObservationWell, property set extension can be adopted, named Pset_WaterObservationWellCommon, for further information please refer to Appendix B.

For drilling hole sampling entity IfcGeologySample, property set extension can be adopted, named Pset_BoreholeSoilSampleCommon, for further information please refer to annex A. For stratum entity IfcStratum, it attributes information are mainly stratigraphic distribution information and physical-mechanical properties information, property set extension can be adopted, named Pset_StratumCommon and Pset_StratumSoilProperties, for further information please refer to Appendix B.

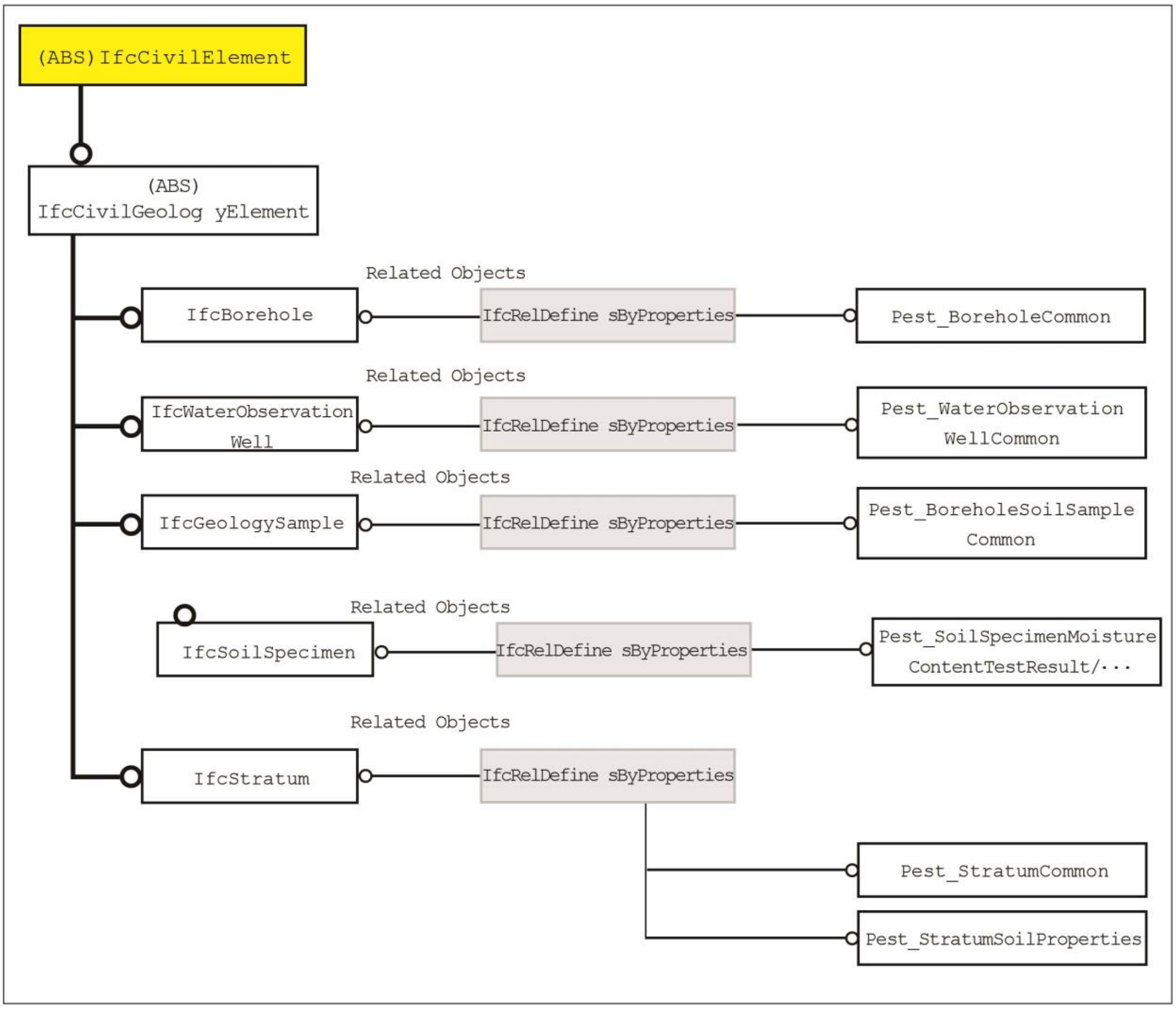


Figure 17 IfcCivilElement extension

Laboratory tests are the tests conduct on the sample taken from drilling hole. Drilling hole sample—IfcGeologySample is derived from IcBorehole, these connections between them can be described through IfcRelAssignToProduct, meanwhile, the SoilSamples in the IfcBorehole property set Pset_BoreholeCommon would document all the sample codes. The unique code of each sample group corresponds with IfcGeologySample instantiation.

Pset_BoreholeSampleCommon can describe detailed information of the sample. Further information can refer to Appendix B.

In the laboratory tests, operators through IfcGeologySample make soil sample--IfcSoilSpecimen for all kinds of soil test. Main process experimental parameters and result information can be described with different property set, usual laboratory test items can accordingly property set is given in table 5. the contents of these property sets can refer Appendix B.

Table 5 name of common lab test property sets

| Lab test item | Property set name |
|---|---|
| Density Test By Cutting Ring Method | Pset_SoilSpecimenDensityTestByCuttingRingMethodResult |
| Density Test By Wax Sealing Method） | Pset_SoilSpecimenDensityTestByWaxSealingMethodResult |
| Particle Analysis Test By Sieve Method | Pset_SoilSpecimenParticleAnalysisTestBySieveMethodResult |
| Particle Analysis Test By Densimeter Method | Pset_SoilSpecimenParticleAnalysisTestByDensimeterMethodResult |
| Moisture Content Test | Pset_SoilSpecimenMoistureContentTestResult |
| Liquid and Plastic Limit Test | Pset_SoilSpecimenLiquidAndPlasticLimitTestResult |
| Shear Box Test | Pset_SoilSpecimenShearBoxTestResult |
| Triaxial Consolidation Test | Pset_SoilSpecimenTrialxialConsolidationTestResult |
| Consolidation Test | Pset_SoilSpecimenConsolidationTestResult |
| Static Lateral Pressure Coefficient Test | Pset_SoilSpecimenStaticLateralPressureCoefficientTestResult |
| Unconfined Compression Test | Pset_SoilSpecimenUnconfinedCompressionTestResult |
| Penetration Test | Pset_SoilSpecimenPenetrationTestResult |

As for the in-situ information, the main process experimental parameters and result information use different property set to describe. In situ tests used to conduct in the bottom of the pit or drill hole, for former, the connection between test information property set and IfcStratum can be built directly so that could refer that the in-situ tests are conducted in the statum., and for latter, it could connect to IfcBorehole, like Figure 18 shown.

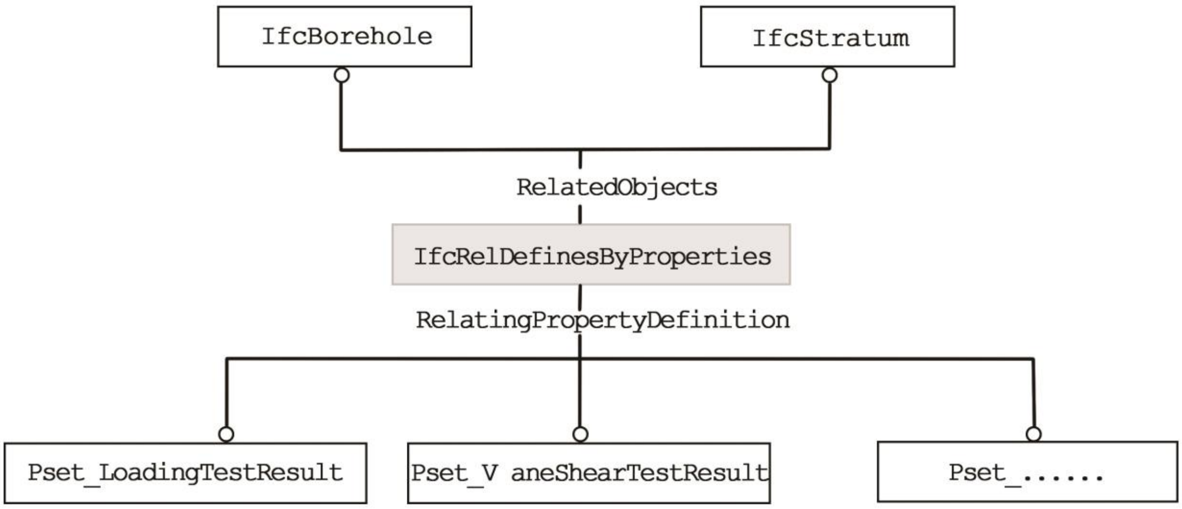


Figure 18 in situ test information model frame

For in situ test information, property set extension can be adopted as well. Based on the in-situ information requirements analysis before, the common in situ test items and their corresponding property set are given in table 6, for further details check the appendix B.

Table 6 name of common in situ test items property set

| In situ test item | Property set name |
|---|---|
| Standard Penetration Test | Pset_StandardPenetrationTestResult |
| Cone Dynamic Penetration Test | Pset_ConeDynamicPenetrationTestResult |
| Pressure meter Test | Pset_PressuremeterTestResult |
| Cone Penetration Test | Pset_ConePenetrationTestResult |
| Loading Test | Pset_LoadingTestResult |
| Dilatometer Test | Pset_DilatometerTestResult |
| Vane Shear Test | Pset_VaneShearTestResult |
| Field Direct ShearTest | Pset_FieldDirectShearTestResult |

**4.1.2 Spatial zone element**

Spatial zone element is the spatial zone of a physical element, these two elements have a relation of spatial containing. IfcSpatialZone entity describes the space with specific functions, in the IFC standard, it is the spatial zone of IfcCivilElement. Therefore, this thesis derived IfcGround entity from IfcSpatialZone, which can be regarded as tunnel project using ground, this zone entity contains all the geographic physical element. IfcRelContainedSpatialStructure is used to express the spatial containing relations between spatial zone element and physical element, the other property RelatedElement express the physical element contained in the zone. Borehole entity (IfcBorehole), stratum entity (IfcStratum), water observation well entity (IfcObervationWell) is all linked to IfcGround which is contained by it through IfcRelContainedInSpatialStructure.

Furthermore, sample information (IfcGeologySample) is sourced from geological drill hole

(IfcBorehole), the relation between these two is usually many-to-one relations, and such relation is expressed with relation assignment entity (IfcRelAssignsToProduct). The RelatingProduct property of IfcRelAssignToProduct refers to linking object(IfcBorehole), RelatedObjects means the linked object(IfcGeologySample). The details are shown in Figure 19.

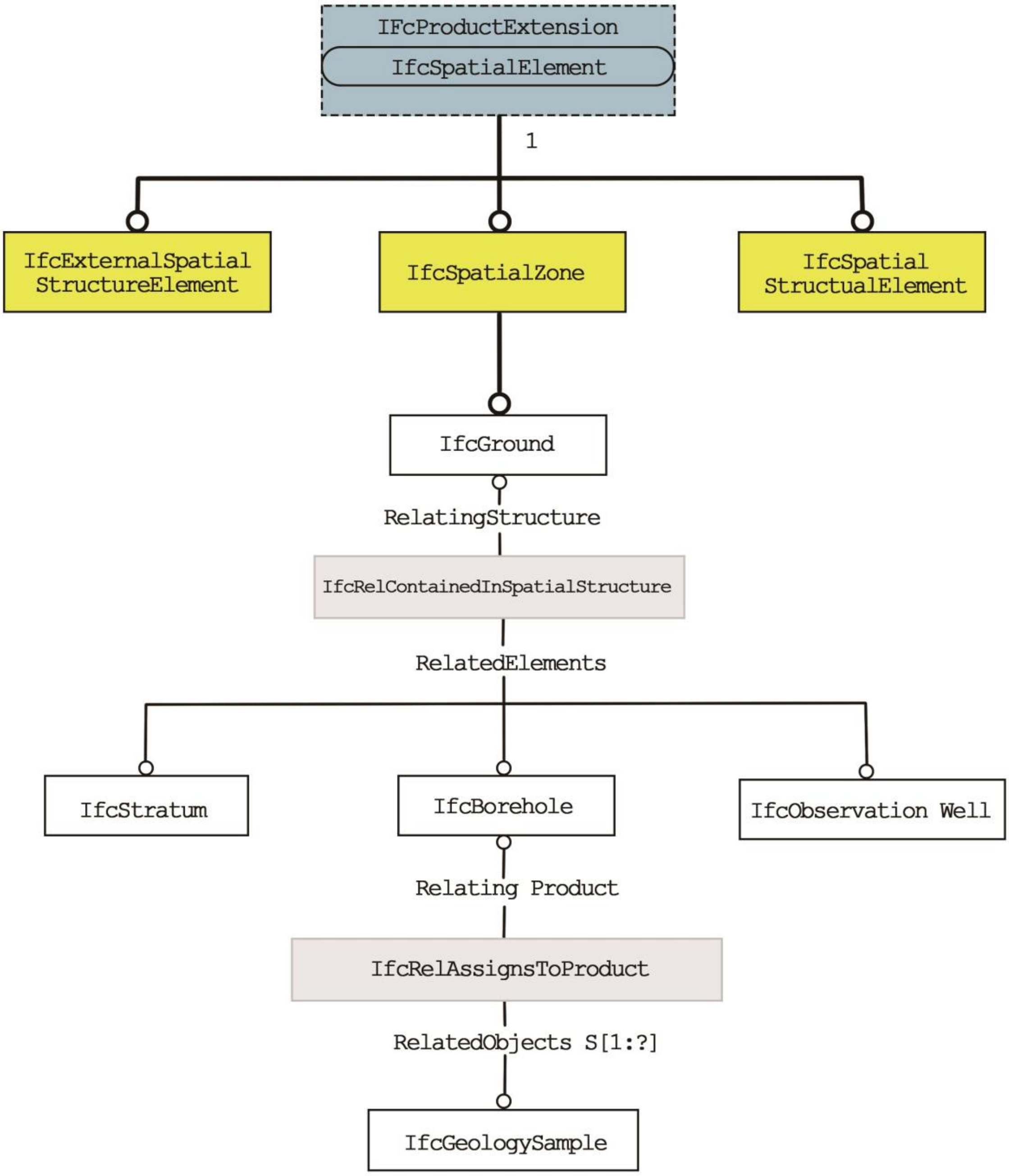


Figure 19 Geological survey information model frame

### 4.2 Detailed extension mechanisms comparison

The four common extension mechanisms for BIM model have been fully and accurately introduced in Chapter 3, and briefly discussed pros and cons in theoretical aspects. However, the more accurate comparison needs to be discussed, since in the different cases, their behavior would differ. This part specifically discussed four mechanisms from the ease of implementation, ease of use, expressivity and performance in the context of geological data extension for shield tunnel BIM model. These can be referred in the tables below.

**XML**

Table 7 evaluation of XML in the geological data extension context

| | |
|---|---|
| Ease of Implementation | It is actually quite easy to implement when cross industry involved, and for the geological survey phase, there are indeed different domains involved as we discussed before, also most of softwares the involved parties using have a built-in function of transforming into XML |
| Ease of use | It is easy to use this mechanism since the XML extension is not a complex mechanism, people, companies, machines could all achieve storing, exchanging, sharing data easily. And easy to understand the mechanism. However, the file size of it would be huge when it used in the huge projects, which would cause troubles. |
| Expressivity | Expressivity is not good enough, it is sometimes insufficient to describe the complexity of building project. And tunnel project is more complicated than the building above the ground, we also explained it before. And the main complexity is from the geological survey phase. |
| Performance | Will not be excel performance in the case of geological survey, since the data from this phase is frequently used later on, and changing dynamically later on, these data need to be understand in the better way since it influences the whole project a lot. Extension model based on XML technology fail to meet these requirements |

**Solely using proxy extension**

Table 8 evaluation of solely using proxy in the geological data extension context

| | |
|---|---|
| Ease of Implementation | Like aforementioned, quick implementation, since it is able to extend the scope of IFC without changing the schema, but require additional implementation agreements about the meaning of properties and proxies if they shall be shared with other CAD software. As mentioned, there would be many |

| | |
|---|---|
| | parties involved and it is hard to guarantee that they would share the same software since they are from different domain. So, the actually implementation is not that easy. Also, the users do need the easier tools to add new proxy, which means it is not easy. |
| Ease of use | When using it, within few stakeholders involved, it is easy to use it since there would set agreement in case a huge number of proxy classes could lead to conflicts regarding element identification, since different team members could use different names for identical or similar elements. individual aspects of a tunneling project, for example. the ground, the tunnel or the TBM should be integratable into one IFC file. If each element of each aspect is represented by separate proxy class, this can lead to great confusion. |
| Expressivity | using proxy and user-defined elements are not definitive and robust, which could lead to errors, ambiguities based on our previous research, there are massive elements and many aspect of these elements need to be expressed, which would arise confusions |
| Performance | It is easy to find out that this extension would not stand out in the case of geological survey since there are plenty of elements and their aspects proposed to add in the extension. And multiple users would access to the data for the following work. The ambiguities and confusion this extension caused would affect the its performance. |

**Ad-hoc heterogeneous data**

Table 9 evaluation of ad-hoc heterogeneous data in the geological data extension context

| | |
|---|---|
| Ease of Implementation | To implement this mechanism is even more difficult since there is certain mount of stakeholders involved in the geological survey early phase, but more stakeholder will involve later on. And they would model their own domain, organization structures. Compared with the effort they would spend on reaching agreement, they would prefer alternatives. |
| Ease of use | Using this extension mechanism is easy, but the limitation is that different projects like BARBI or LexiCon, they are built based their national classification standards and their native languages. Such as BARBi in Norwegian and LexiCon in Dutch. So, it would be a problem for some stakeholders out of their region to use. |
| Expressivity | This allows the computer to fully understand a building information model, helping on many tasks of its users. Even those benefits will be only available in countries that have |

| | |
|---|---|
| | developed an implementation of IFD (or cooperated on international efforts like the IFD Library), because of its very regional character. Still, i would argue expressivity of ad hoc fashion is preferable. |
| Performance | As for the performance in the case of geological survey for tunnel project, it would not be ideal due to some issues. There are some similar concepts or same concepts required by different domain stakeholders, as a consequence, the duplicate concepts and their relations would pollute the library, arise contradictions and inconsistency between different items in the vocabulary. Moreover, the lower technical levels such as transaction safety are depending on the underlying implementation of vocabulary system. |

**The Linked Data**

Table 10 evaluation of the Linked Data in the geological data extension context

| | |
|---|---|
| Ease of Implementation | The Simple Protocol and RDF Query Language (SPARQL) provides a mechanism to expose such data sets and vocabularies in straight-forward and affordable ways as so-called 'SPARQL endpoints'. Therefore, with SPARQL, implementation is relatively easy, quick and realistic. |
| Ease of use | The 'Anyone can say Anything about Anything' (AAA) principle is of the fundamental notions of the Semantic Web and Linked Data efforts, which perfectly suite the case of tunnel project geological survey situation. Different domains could work their own things out and share, expose their views with as a low a threshold as possible that can be used and interpreted with as little effort. |
| Expressivity | The Web Ontology Language (OWL) is, like RDFS, an extension of the RDF. OWL is an ontology language that offers a greater expressivity in object and relation descriptions by enabling efficient representation of ontologies that are amendable to decision procedures |
| Performance | This extension to the discussed case would perform very well since it indeed avoids the limitations of other alternatives, also it is able to meet all involved stakeholder's requirements. |

After all these discussions, the Linked Data is the desirable mechanism to extend the IFC shield tunnel model in the end. However, IFC databases are not based on Semantic Web data sets like RDF or OWL data, but on the EXPRESS modelling language. IFC databases can therefore not be directly connected to Semantic Web technology without converting an IFC schema into an OWL ontology, which is considered to be straightforward except for some minor complications. Still, IFC can benefit from the advantages of Semantic Web related technologies due to the possibility of converting IFC into OWL files.

## 4.3 Methodology

After the thorough and comprehensive extension mechanism comparison, the Linked Data is evaluated as the most appropriate approach to extend the geological survey data in the case of metro station/tunnel. This part focuses on describing the technical developing process for the IFC extension by using Linked Data. The methodology is present in Figure 20 below. The whole technical process includes five major parts as shown. Each part within the process is divided into several steps. All the involved steps are introduced following.

### 4.3.1 Data Collection

As the first step of extending IFC shield tunnel with the Linked Data mechanism, it is crucial since it has an obvious effect on the not only results but also process. For instance, different data sources would determine the use scenarios, and the tool of conversion, the complexity of conversion process would have been determined when the data source is certained.

**Data sources selection**

Normally the main criterion for data selection is meeting end user's information needs, in this case, it is supposed to be the designers who are going to design a new project surrounded the existing building project. Such as, there is metro tunnel underground, and another building would be conducted sometimes just above the tunnel, and other times may very close to the tunnel. Since the geological data is the public open source, they are able to spare time searching it. However, the foundation treatment or the monitoring plan which are made for the "existing tunnel" from a certain metro tunnel contractor are not "open sources". In fact, the designers for the new planned building normally would check the metro tunnel model to integrate their design. In this specific case, the monitoring data of ground settlement could meet designers' needs. Apart from that, the accuracy, continuity and stability of the data are crucial criterion beyond question. The synthesis of these criteria would help selecting suitable data sources for later integration. To well serve the end users' needs, not only required direct data, but also auxiliary and exegetic data that supports those direct data should be collected.

**Data obtaining**

Data obtaining refers to finding correct channels to receive the data. Most of the public domain data resources can be obtained without obstacles, but some private or organizational owned data may have extreme identity requirements. Also, the forms that information extracted from are various, it could be a file, online, database, etc. Then the key point is how to find a suitable data-saving method based on different forms. Data obtaining also means collecting data with legal clearance. Authoritative data publishers possibly provide different applicable licenses for different end users, serving various purposes and supporting distinct processing method. In case the conflicts and liability, it is necessary to identify the authoritative data publishers and related data using license.

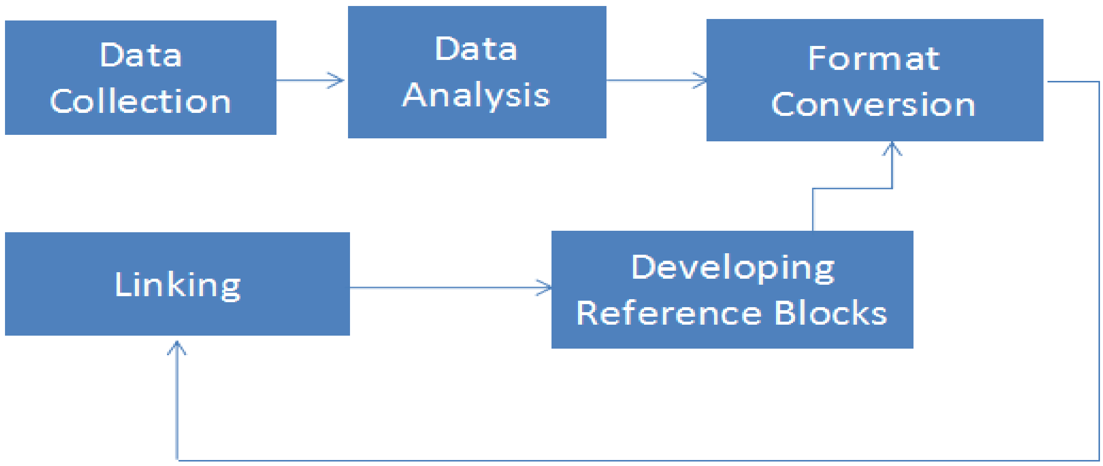


Figure 20 Technical process of extending IFC shield tunnel

### 4.3.2 Data analysis

After the data resources are ready, looking into datasets thoroughly as preparation for data conversion is the second step.

**Data structure analysis**

Data analysis would always start with what the structure of datasets is and how they organize. The obtained datasets may have heterogeneous formats. Also, to get more insight about provided information form. For the later use with Linked Data extension mechanism, some files need to be converted so that could be processed further, such as csv to ttl or RDF/xml, rvt to ifc and to RDF/xml, etc. The preferred data formats will be determined based on data organizing structure and other linking data sources.

**Obtaining data schema**

Obtaining data schema aims at having a basic understand of the various data-sets major concepts, as well as information overlap and expression differences. Analyze the “links” among different major concepts to develop a combined relational graph—ontology. This could help performing the following conversion and linking tasks, meanwhile evaluate if joint data can meet the end users’ specific information needs.

### 4.3.3 Format Conversion

The data conversion is actually about converting data into Linked Data way, which is RDF format, for the purpose of data linking preparation.

**Uniform Resource Identifier**

Berners-Lee referred in the four main principles of publishing Linked Data, Uniform Resource

Identifier is required for naming things (Linked Data, 2006). For the URI naming, there are several forms and guidelines. For instance, Radulovic et al mentioned 2 basic forms of URI-hash URI and slash URI (Radulovic et al, 2015). There are also different guidelines for helping URI design, like 10 rules for persistent URIs (SEMIC, 2012), and Providing and Discovering URI Documentation (Rees, 2012). However, for selecting a basic form of URI, the advantages and disadvantages of each basic form and also the preferred URI form for the data transform tools that will be used afterwards will be considered. Besides the URI forms, clearly and succinctly showing the relationships and hierarchy between various resources is essential for URI design as well.

**Ontology Development**

Ontology is a formal specification of a shared conceptualization (Gruber, 1993). In computer science and information science, it is used to name and define types, properties, and interrelationships of entities from a particular domain. Radulovic raised seven steps to develop a well-designed ontology (Radulovic et al., 2015). The main idea of his ontology development method is referenced in this ontology developing step.

Developing ontology to describe resources and relationships from a merged domain starts from considering the overall data content and structure, as aforementioned, in order to grasp the main concepts forming the ontology and their connections. After that, a search for existing ontologies and the selection of some of them for reuse should be conducted. Reusing existing ontologies can help building a new ontology structure and makes the new ontology more accessible. For the information not defined in the existing ontologies, new classes or properties should be created to represent it.

**Convert file format and merge common format file**

The resources naming and ontology developing are all preparing for the transformation step. As Radulovic et al. suggested, select a RDF serialization (RDF/XML, Turtle, N-Triples etc.) as the transformation format. Then select the suitable transformation platform (converter) to achieve the RDF conversion based on the input and output data formats that the IT tools support. Since data sources may be collected with different formats with different formats, like a spreadsheet, XML, and IFC, several transformation tools may be needed. After selecting the tools, transform those to RDF format, and merge the transformed RDF files into one model. This can be produced through Java RDF API or other software like Google Refine. The evaluation of the converting file format and merging common format file can be executed by SPARQL queries in the following part. If the SPARQL queries go smoothly and get correct results, the file format converting and merging works well.

### 4.3.4 Linking

Linking aims at creating links between the RDF data that comes from different data sources. The data resources' content analysis and schema extraction have been performed in the data conversion part. Full preparation has been made for the data linking.

**Identify linking objects**

The RDF data from different data sources are isolated in the merged model. Selecting linking objects depends on the goal of performance tasks that demanded by end users-designers. The created links would help users to navigate end users traveling through the different information islands to the required information. Regards ontology, direct and simple links among dissimilar RDF data is the basic rule for identifying linking objects.

**Relations clarification**

After identifying linking objects, clarifying resources relations through suitable properties would be the following step. The property selection can take a reference of existing ontology vocabularies. If existing properties fail to meet the satisfaction, then new properties would be created into existing class.

**Semantic Web applications constructing tools selection**

There are certain tools creating links among RDF data, such as Google Refine, Jena Apache API, Fuseki, TDB, etc. Different tools have different data requirements and function configurations, like RDF serialization limitation, data structure requirements and data size requirements. Selecting a suitable tool based on the data attributes can simplify the linking process.

### 4.3.5 Developing reference blocks

The reference design reflects end users' demands, in this specific case, it is the monitoring information of surrounding metro projects. It is designed based on available data and user demands that help managers to grasp monitoring plan, drill hole types and sensitive area. Every query performs a specific topic. All the composed coding components for this reference topic are collected as a whole and called 'reference block', as a packaged block, the package is more convenient than shattered codes for designers to use. The reference blocks conduct SPARQL queries, also the query results would be used to do calculations.

SPARQL queries can be regarded as a form of evaluation about the results from data conversion and data lining parts. It could help testing whether the ontology design is feasible, whether the RDF data transformation performs well enough to show the needed data structure, whether the merging and linking work well, etc. As long as this test reflects problems regarding the previous parts, then iteration back to the conversion and merging is necessary.

**Topics selection**

The data sources in this research are sensor data, drill hole description and a BIM model. The end users are the new project designers. The research aims at helping new project designers referencing shared monitoring plan and new project design, also helping project manager monitoring the building structural features during construction of surrounding project. Through the interview figuring out designers' possible information demand based on sensor data and building information would be the basement for designing reference block. After detailed demand analysis, several new-project-designer-caring topics are selected.

**Developing SPARQL blocks**

After reference topics are selected, developing the SPARQL blocks would be necessary. The blocks include the SPARQL query part and the query results processing part. The SPARQL query part extracts information among direct or indirect resources relationships. The query results processing part performs further data deductions with the supports from other domain or data processing methods to help designers starting new projects. The different blocks are based on different reference query topics.

## 5. Case Study

This part is going to illustrate an actual case application with the aforementioned methodology, which aims at achieving extend geological survey data into IFC shield tunnel model through Linked Data approach.

The adopted project is called 'DongJing Station'. It is a metro station of metro line 9 in Shanghai, located in Songjiang District, in which area, there would be tremendous building projects developed in the future due to the process of Shanghai urbanization. As shown in the figure below, the project located in the Southwest of Shanghai.


Figure 21 Location of Dongjing station

Figure 22 shows the landscapes of Dongjing station surrounding area and an urban area of Shanghai, which can be seen from the figure that normally the urban area is supposed to build massive buildings, however, the Dongjing station surroundings holds the huge vacant area that needs to be developed later on. As matter of fact, the government did have plans to set more commercial, educational and living facilities there as part of Shanghai urbanization.


Figure 22 The landscape of Dongjing station surrounding area and Normal urban area in Shanghai

The metro station is already there, there has been massive information collected regarding the geological survey, experiment and monitoring. Such information can be shared with will-be-developing projects in the surrounding area. In this case, the station is selected as the research object; the figure below shows the Dongjing station model.

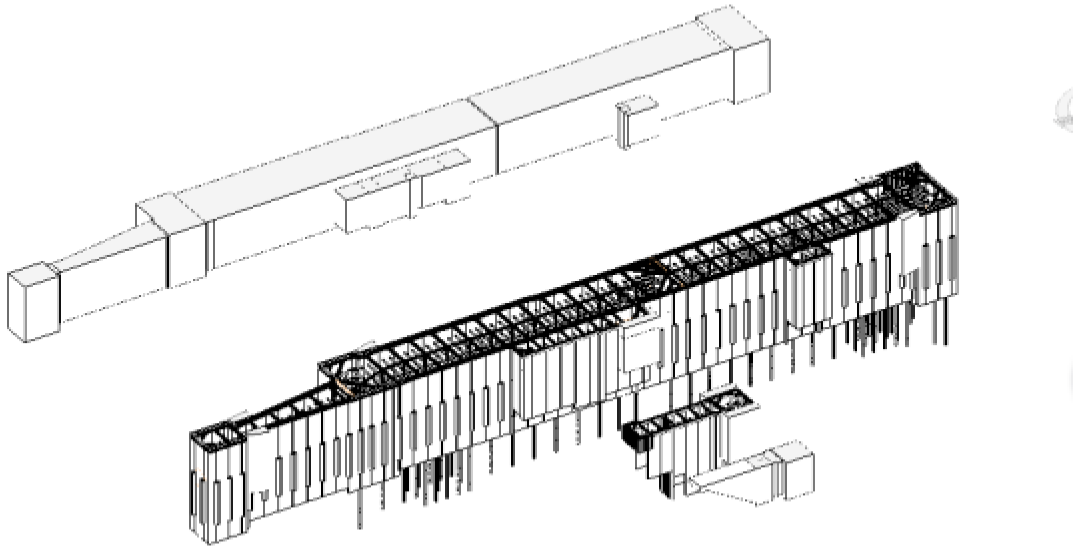

Figure 23 Dongjing Station IFC model

The complete process of case application is shown with BPMN, as

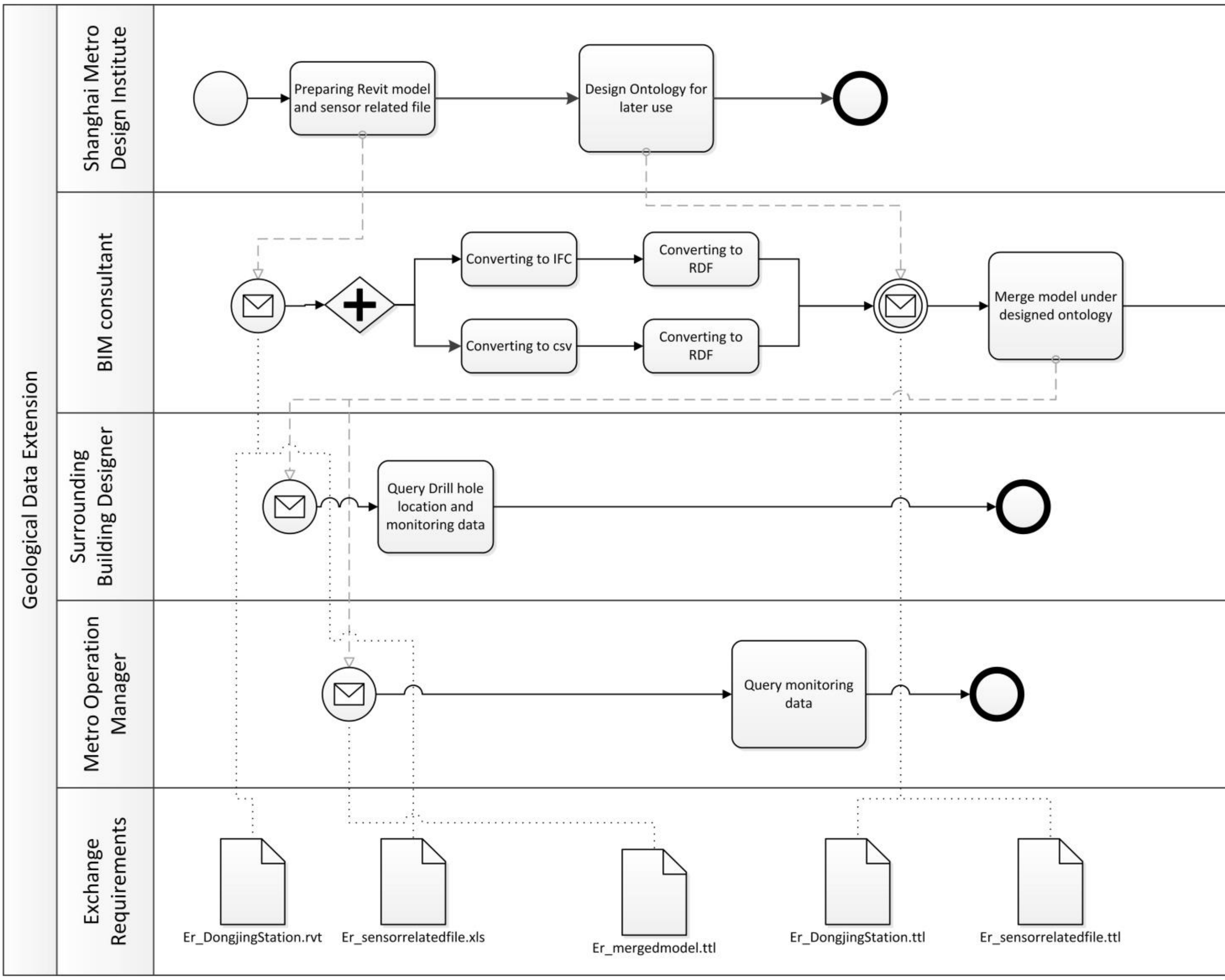
Geological Data Extension
Shanghai Metro Design Institute
Preparing Revit model and sensor related file
Design Ontology for later use
BIM consultant
Converting to IFC
Converting to RDF
Converting to csv
Converting to RDF
Merge model under designed ontology
Surrounding Building Designer
Query Drill hole location and monitoring data
Metro Operation Manager
Query monitoring data
Exchange Requirements
Er_DongjingStation.rvt
Er_sensorrelatedfile.xls
Er_mergedmodel.ttl
Er_DongjingStation.ttl
Er_sensorrelatedfile.ttl

Figure 24.

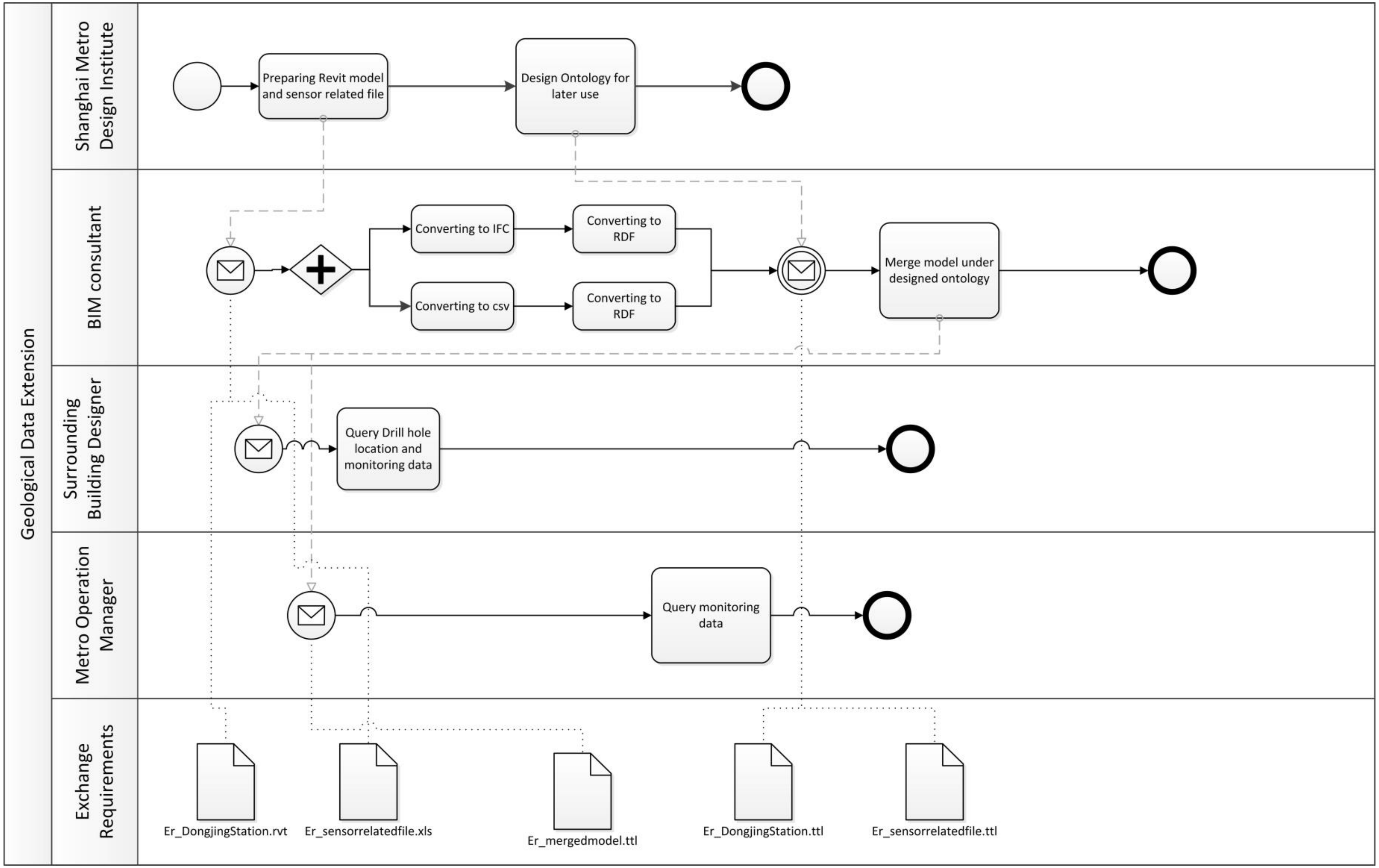


Figure 24 case study process

## 5.1 Data collection

For the Dongjing station case, the new ontology and linked merged model is designed to facilitate designers of surrounding project to design their building with the metro station monitoring information. Different types of new building project with potential influence from dynamic geological data are assumed to be the user information demands for new designers. So, sensor data and geological data are supposed to be both general and specific and a BIM model is used to present the related structural components context.

**Data Sources Selection**

There are 9 monitoring items designed for existing station. The initial total number of the sensors for 9 monitoring items was 1330. The 46 sensors to monitor soil layered displacement, the 47 sensors to monitor rip of retaining wall system, the 591 sensors to monitor bolt pulling force, the 7 sensors to monitor excess pore pressure, the 324 sensors to monitor deep lateral deformation of the soil, the 136 sensors to monitor horizontal displacement of the top of the retaining wall, the 136 sensors to monitor vertical displacement of the top of retaining wall, the 18 sensors to monitor water level and the 31 sensors to monitor ground settlement. Water level monitoring and ground settlement monitoring are selected as data sources since they are different from other monitoring items that are limitedly tightly linked to the project itself and hard to connect to other surrounding building, and these 2 monitoring items are very directly linked to the new surrounding projects, in other words, sensors' measurement meet the designers' information needs. Therefore, there are 31 monitoring points with 31 displacement sensors and 18 monitoring wells with 18 water level sensors. Since the water level monitoring plan and ground settlement data from the Dongjing station are already available, also these collected data could help designers. The sensors of these two items are equipped with the drill holes. Moreover, to make this information easy-understanding and query (referenced), drill hole description regarding the types, locations and etc is added as supplementary data for those sensor values.

Meanwhile, a BIM model is needed to present the station space context. The model is requested from the Shanghai tunnel design and research institute.

To conclude, all the data sources for the later integration process are listed in Figure 25.

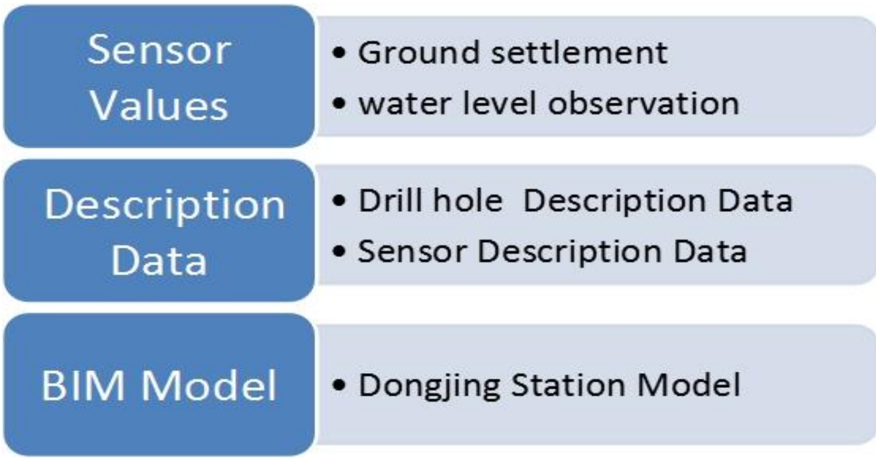


Figure 25 data sources

**Data obtain**

Sensor values of ground settlement and water level observation are obtained directly from Shanghai institute, the sensor data is saved as a local excel. Due to the confidential issue, the access to their database is denied, the sensor data is received directly. Main indicators of water level sensor are given in Table 11. For the complete set of water level monitoring data and ground settlement monitoring data can refer to appendix F.

Table 11 partial main Indicators of SW1

| | |
|---|---|
| Range | 0-30m |
| Variation in measurement values | ±0.25% |
| Resolution | 1cm-1dm |

The drill hole description file is generated from project manager’s monitoring plan, which is also an excel file as Figure 26 shown. The Excel file mainly focus on location descriptive data, which is the necessary information in the domain of geological data. More details can refer to appendix F.

| Drill hole type | Elevatior | Depth(m) | Coordinate X | Coordinate Y | Settle water level monitoring sensor | Settled ground settlement monitoring sensor |
|---|---|---|---|---|---|---|
| static penetration test hole | 5.28 | 25 | -2537.31 | -17964.77 | SW1 | W1 |
| static penetration test hole | 5.24 | 25 | -2605.77 | -18022.74 | SW2 | W2 |
| static penetration test hole | 4.66 | 50 | -2670.12 | -18181.11 | SW3 | W3 |
| static penetration test hole | 4.43 | 55 | -2854.76 | -18240.59 | SW4 | W4 |

Figure 26 example partial data set of DHD

The BIM model for Dongjing station is created through Revit and received directly from Shanghai metro design and research institute. The model itself is shown in figure 21. It can be seen that the site related information is not saved in the model. For instance, the drill hole, as a part of the project, which can also be seen as a “building element”, is not contained in the BIM model, also the location of these holes are shown in the model.

### 5.2 Data analysis and format conversion

The data analysis and data conversion are combined together in this part. These two procedures are coordinated for the aim of creating a well merged RDF model.

**Resources naming strategy definition**
Open refine is selected to convert the csv file to RDF file. OpenRefine is a powerful tool for working with messy data: cleaning it; transforming it from one format into another; and extending it with web services and external data (Openrefine, 2016). The Figure 27 drill hole description, and the detailed process of converting csv file to ttl file in open refine is shown in appendix D.

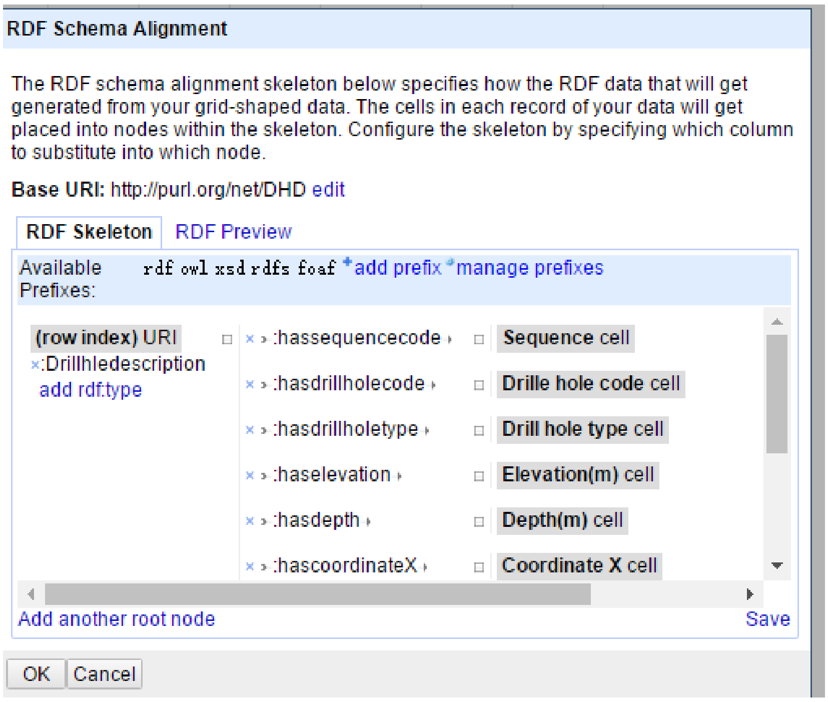

Figure 27 converting drill hole description csv file to turtle file in Open Refine

In this case, an ontology describing drill hole description would be published, so the chosen name is Drill Hole Description ontology (DHD to keep it short). The technical support for defining URI is given followingly.

Since there are certain potentials to publish the ontology, the chosen URI should be permanent and defined in a domain I control. To prevent certain usual case, somebody is reusing the concepts defined in my ontology and I changed its URI. The person reusing my ontology will no longer know the proper definitions and semantics of the reused term. And I assume that most of people reading this are not willing to pay for a new domain each time a new ontology is published. Therefore, I define the URI of my ontology in http://purl.org. PURL stands for persistent uniform resource locator; they are widely used to give persistent URIS to resources. The assumption of this part is that I registered in the page, and I started directly defining a new domain, waiting for the approval and create the URI for my ontology. As a consequence, in my case it is http://purl.org/net/DHD. I created the name under the /net/ domain; things would go faster since it is the default domain. Otherwise they will have to approve the domain and the name of my ontology. Then hash URI is chosen due to the following reasons, the information is easy to publish using an editor for RDF files, with slash, the server may need to be set up to do a 303 redirect from the URI for the thing to the URI for the document about it. This involves control of the web server which many people do not have, or have not learned to do; also, the run time speed is another factor which is considered, the client looking up the URI just strips of the right part, and performs a single access to get the document about whatever it is. This will in many cases also give information about other related things, with URIs starting with the same document URI. Further fetches will not be necessary at run time (W3C, 2016). The naming path for the drill hole description data begins with 'http://purl.org/net/DHD#', and concatenates with described items. The naming path for the geo sensor data begins with 'http:// purl.org/net/Geosensor#, then continues with the items to be described. The resources and properties related to the BIM model will be named automatically by the RDF transformation tool. All these sensors' and BIM model's resource and property names are only used as unique identifiers.

**Ontology development**

Since the main idea of the collected data is about sensor data and building geological data, the developed ontology should also focus on describing the entities and relationships between building site and sensor data. The Smart Appliances REFerence(SAREF) ontology is a shared model of consensus that facilitates the matching of existing assets model of consensus that facilitates the matching of existing assets in the smart appliance domain. The SAREF ontology provides building blocks that allow separation and recombination of different parts of the ontology depending on specific needs (Smart Appliance, 2013). Also, IfcOwl ontology is used to describe IFC-based vocabularies. To conclude, including the basic OWL, there are three existing ontologies applied in the case study's ontology for the geological survey data extension, as Figure 28 shows below.

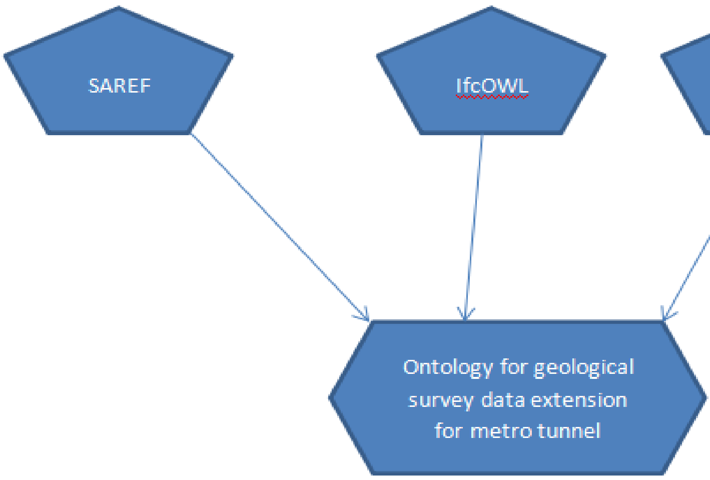


Figure 28 model ontology composition

Additionally, these three existing ontologies fail to suit the case perfectly, since the related drill hole descriptive data and sensor descriptive data have not defined. Therefore, the new ontology which contains the new classes and properties to illustrated the related sensor values and drill hole description data. For instance, Data property Drill hole: drillholeDepth is added to the ontology to introduce the different depths in the drill hole description file. Class drill hole: drillhole is added to the ontology to introduce a is a narrow shaft bored in the ground, either vertically or horizontally for specific engineering use, in the case, we considered it as a container for sensors. Property sensor: accommodate represents the relation between a sensor and the location (drill hole). A file describing the RDF ontology schema for the self-created classes, individuals and properties are put in appendix E.

Figure 29 ontology before linking is created to shown the main part of the united ontology. The straight arrow represents the relationship between classes, and the dash arrow shows the relations between the class and individuals (which are not shown in the figure due to the size limits). The color green, yellow, blue, orange, light green represents different ontology: sensor description (SD), saref, drill hole description (DHD), sensor value (Geosensor), and building model. The clearer separated ontology is given in appendix E.

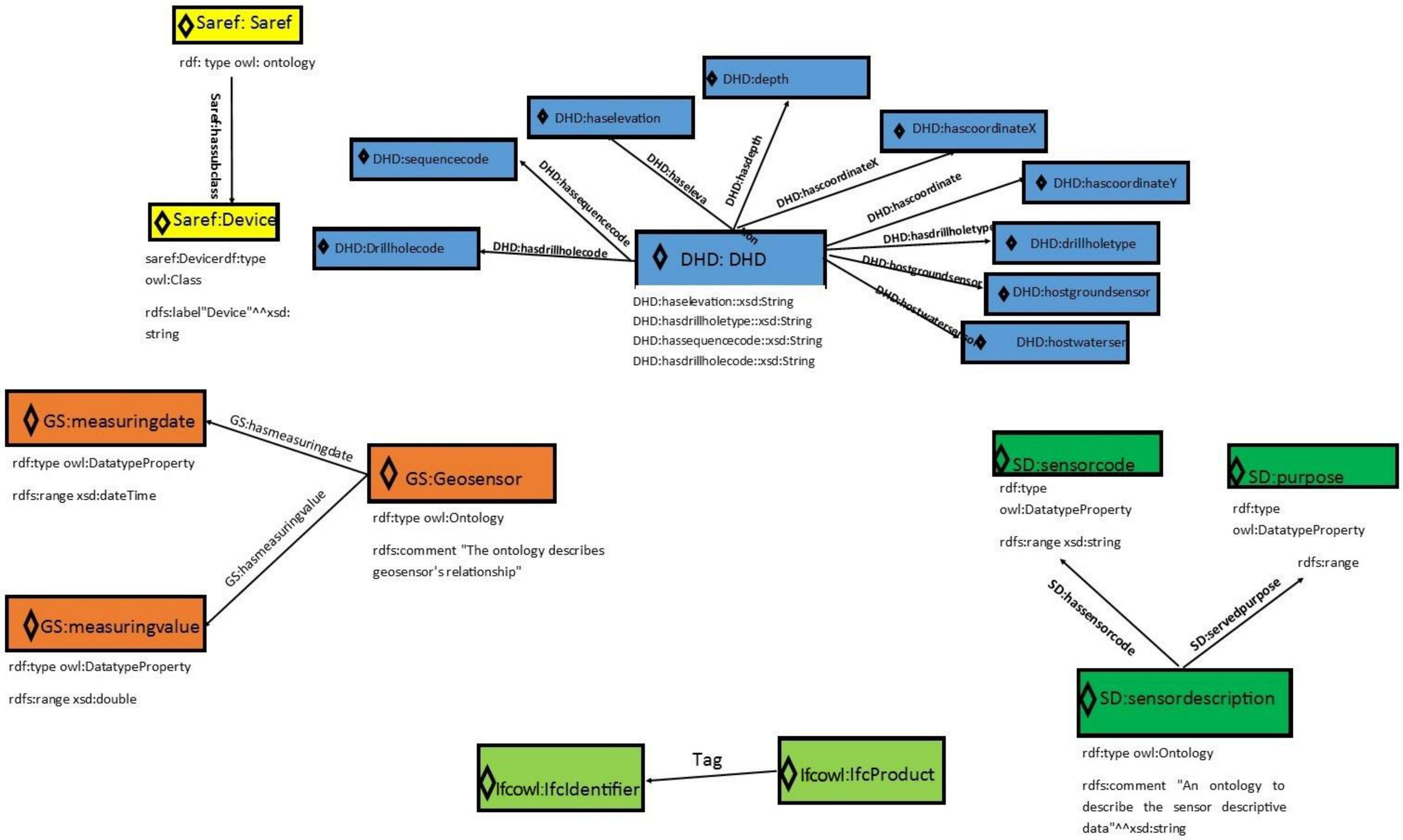


Figure 29 ontology before linking

### 5.3 Data sources transformation and merging

The RDF serialization used in this case is Turtle, because of its readable attribute, which is much easier for people to read them. Since the data sources' original formats in this case are heterogeneous, two transformation tools and python script converter are selected to perform the turtle transformation process. The detail process is present in figure 22. The tool used for the data merging is Apache Jena Fuseki, which is a SPARQL server. It provides RDF writing, reading, simple query and other Java-based methods. In the merging data section, it is used to create a model which combines all the turtle data. The Java coding part can be reviewed in the appendix G.

**Data linking**

Even the merged model is created, the data from different sources are still isolated. No path is available to navigate through different information islands. The Linked Data approach aims at connecting related data that has not been connected, to help exploring connected information world. As the ontology development section shows, there are four parts of data in the merged model: the sensor value data, building model, drill hole description and sensor description. In the linking process, drill hole description is in the middle to generate links, as the drill hole description contains resources that have relationships with sensor value and sensor description. The Drill hole description has a class "DHD:DHD" expressing the accommodate attribute in string format, which can make a link with "Geosensor" class in the geosensor ontology, since the "Geosensor" is located in the drill holes. This relationship between these classes is presented by a property named "DHD:accommodate". This link is set to connect according sensors and drill holes. The "SD:sensordescription" class express descriptive data of the geosensors, and these sensors do introduce certain value in the Geosensor ontology. The logic relationship to link sensor description (SD) with Geosensor (GS) is presented by a property named "SD:describe". On the other hands, geosensor is not part of building but it did serve the building, in this situation, the class "GS:geosensor" is linked to "Ifcowl:Ifcproduct" directly to reveal the logic relationship between the geosensor and building model, this relation is set as "GS:served". Though, the ontology "Geosensor" expressed the ontology outside of the building project, it is not contained within building from the perspective of spatial relationship. It is still the sensor served the structural element that is within the building project indirectly. Thus, the property "saref:hassubclass" is set as a link between saref ontology and geo sensor， the set property would connect class "Saref:Device" and "Geosensor:Geosensor". After these connections, the five information islands are integrated as one resource interrelated model. This is preparation for the data query process. The ontology graph with linked relationships is shown in Figure 30. The Java coding to build the links based on Fuseki merged model is also contained in appendix G.

Noticeably, the original links served for sensors and project are supposed to be created between water level sensor and IfcGround, as for ground settlement sensors can be attached to IfcBorehole directly like the aforementioned developed extension. However, in the BIM model offered by Shanghai metro design institute, neither IfcGround or IfcBorehole is created within the model. Still, model validation which is on purpose of verifying the Linked Data approach and the actually developed model needs to be conducted. Thus, the assumptions that the sensors are set to serve the certain structural elements. For example, the drill hole “ZK13”, ZK13 accommodates the ground settlement sensor that has sensor code “W30”. And in the model, there is a drilling pile with Guid “0f5PYVtSrAQgQbS3YOD0$q” and tag “785871”. As shown in Figure 30. The green pile is the selected pile to set the link. Accordingly, there is a unique Ifcidentifier for the drilling pile, which is IfcIdentifier_1954236. The sensor located in “ZK13” serves the pile. Hence, the link between them is set. All drill holes and their related structural elements are given in the appendix K.

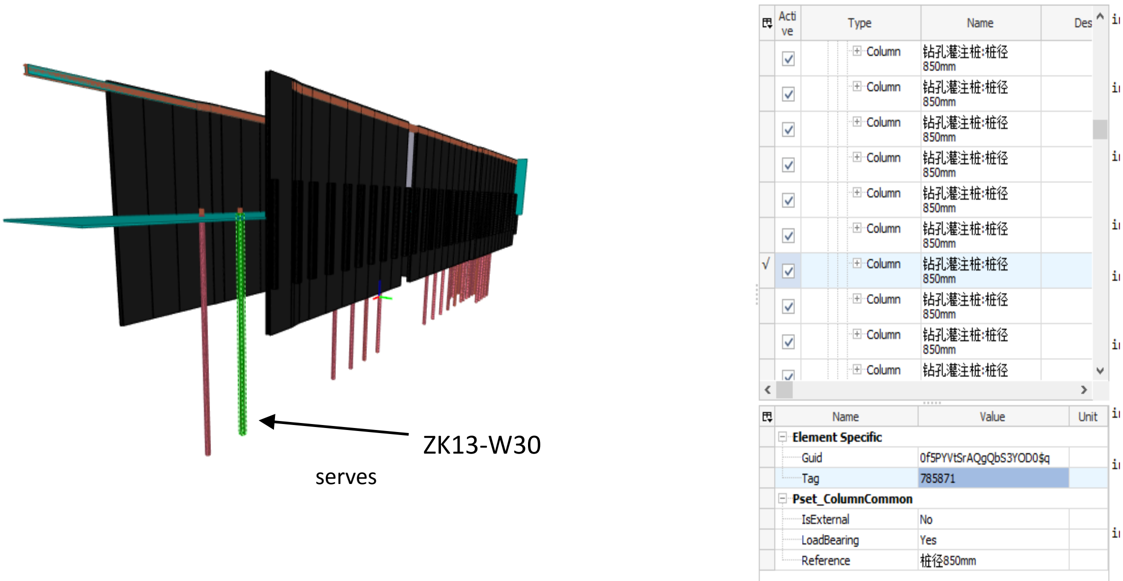


Figure 30 the links between drill hole and specific structural element (image from BIM vision)

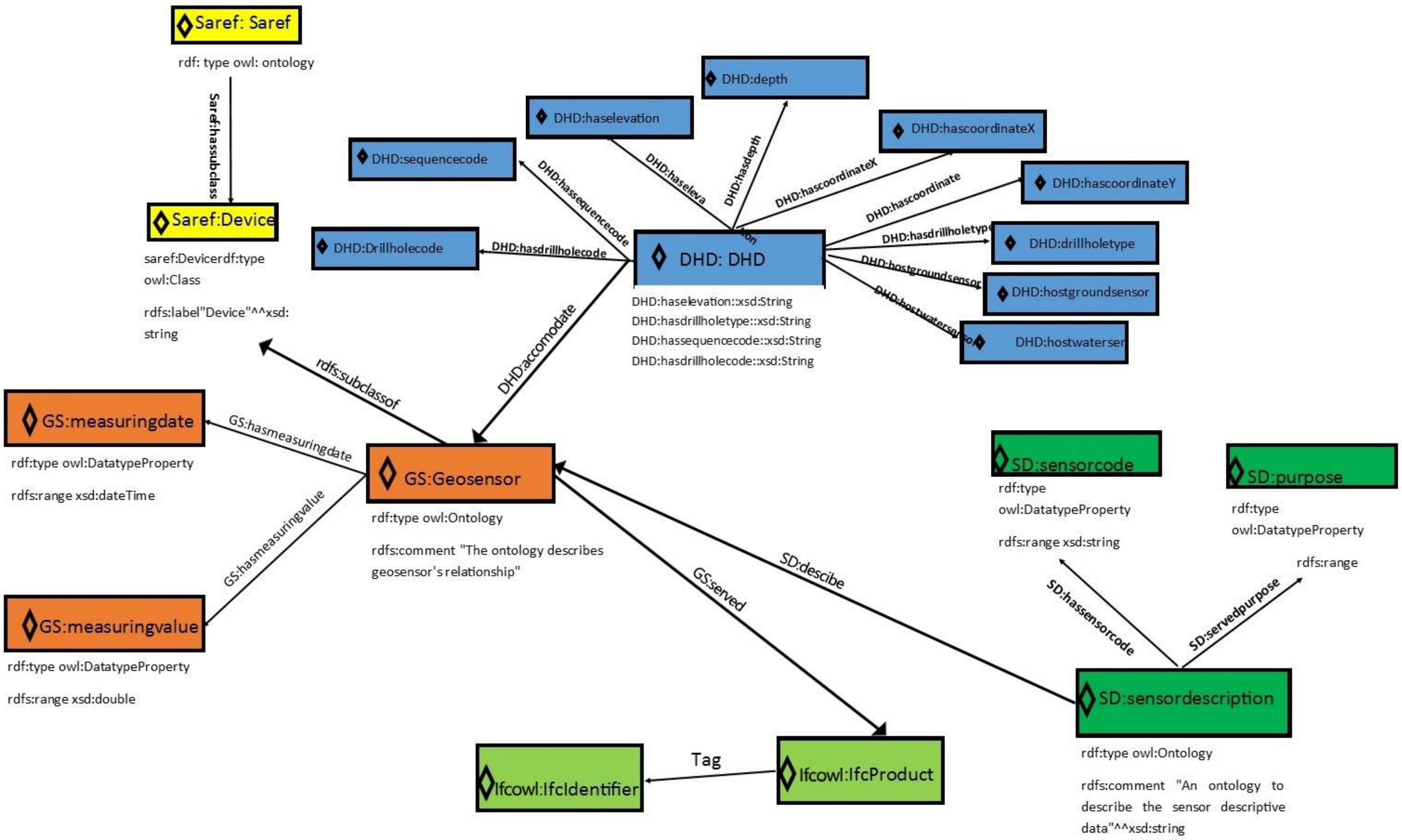


Figure 31 merged ontology after linking

## 5.4 Query

The sensor data and drill hole description documented for integration are about water level monitoring and ground settlement. All the related information could help project manager for surrounding project to manage their own project process, not only early design stage but also the construction stage.

The existing drill holes and placed sensors within a project would be an excellent reference for surrounding project. Therefore, the locations of these drill holes and corresponding sensors are required to print out to master the drill hole plan and monitoring plan. In this case, the location query needs to be development with the SPARQL. This block mainly served the new project manager instead of existing building's facility manager.

However, the drill holes' location is expressed local Cartesian coordinate system, the origin of this coordinate system is the survey point of the metro station, which is presented as IFC site in the file. The IFC site is expressed with a geographic coordinate system which is latitude, longitude and elevation, and the drill holes' location is present with relative local cartesian coordinate value along the X axis, value along the Y axis and elevation. To actually locate the drill holes and corresponding sensors for the use of other project managers' reference, converting drill holes' location from local Cartesian coordinate system to earth coordinate is necessary. After local coordinates calculation with X, Y, the outcome would be again transformed back to earth coordinates system. The equation of these two processes is shown below. And figure 9 shows the relationship between geodetic coordinates and space rectangular coordinate system (Marcin Ligas, 2011).

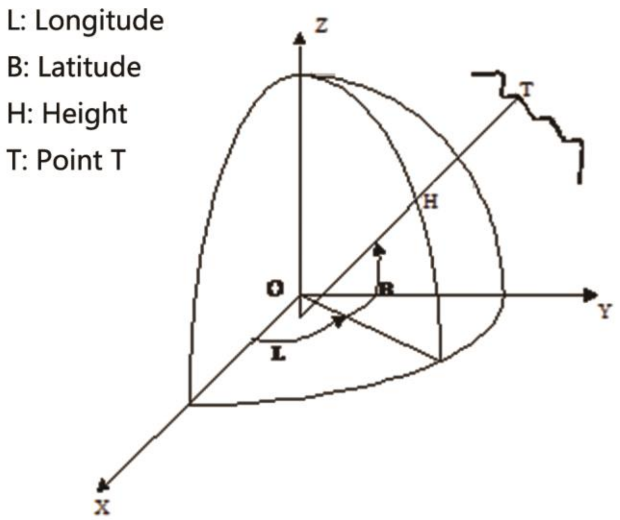


Figure 32 the relationship between earth coordinate and space rectangular coordinate (Marcin Ligas, 2011)

Under the shared origin point, the equations to convert north east down coordinates to geocentric rectangular coordinate are:

$$\left.\begin{aligned}X&=(N+H)\cos B\cos L\\Y&=(N+H)\cos B\sin L\\Z&=[N(1-e^2)+H]\sin B\end{aligned}\right\}$$ (Marcin Ligas, 2011)

In the equation,

$$N=\frac{a}{W}$$ (Marcin Ligas, 2011)

a is the long axis of the ellipsoid, which is the long axis of the earth in this case. N is the radius of curvature of the ellipsoid, which is 6378137 in this case.

$$W=\sqrt{1-e^2\sin^2 B}\ ,\quad e^2=\frac{a^2-b^2}{a^2}$$ (Marcin Ligas, 2011)

e is the first eccentricity of the ellipsoid. B is the short axis of the ellipsoid.
Under the shared survey point, the equations to convert geocentric rectangular coordinate to earth coordinate are:

$$\left.\begin{aligned}B&=arctg\left[tg\Phi\left(1+\frac{ae^2}{Z}\frac{\sin B}{W}\right)\right]\\L&=arctg\left(\frac{Y}{X}\right)\\H&=\frac{R\cos\Phi}{\cos B}-N\end{aligned}\right\}$$ (Marcin Ligas, 2011)

$$\Phi=arctg\left[\frac{Z}{\sqrt{X^2+Y^2}}\right]\qquad R=\sqrt{X^2+Y^2+Z^2}$$

And the converter is written with Java. The Java code can be check in the appendix H. Code for query drill hole location with SPARQL is given in appendix I. Moreover, the disturbance caused by new surrounding projects during the construction stage or design stage would lead to unexpected water level change or ground settlement for the existing, in this case, the sensor measuring data in specific timing is crucial as well. Sensor data querying block is developed with SPARQL is also shown in appendix I.

**SPARQL query example a**

For the purpose of drill hole related data share between the existing project and new developed project, during the stage of design. The shared geological information could facilitate designers' process. Apart from offering related data to designers, but also check the validabilty of merged model. To achieve query, the merged model called "new model.ttl" is uploaded to fuseki server. Firstly, add a new dataset as Figure 33 shows. Then upload merged model in the created dataset. In the SPARQL query, Use SELECT to signify you want to SELECT certain information and WHERE to signify your conditions, restrictions, and filters. In the situation, as a designer who is going to design the building nearby the Dongjing Station, I

would like to know what drill holes are already there serving the Dongjing station, and where exactly they, what sensors are in the holes. This information is given in the drill hole description, therefore, the prefix DHD is set in front as "PREFIX DHD: http://purl.org/net/DHD#". Afterwards, SELECT the certain information, which are drill hole code, coordinate X, coordinate Y, elevation, ground sensor and water sensor, they are set as "SELECT ?drillholecode ?coordinatesX ?coordinateY ?elevation ?groundsensor ?watersenso -r". Using WHERE function to signify conditions, it is supposed to follow structure "WHERE {?subject ?predicate ?object}", so in this case, it is set as
"WHERE {?dhd DHD:hasdrillholecode ?drillholecode. " and since not every drill hole contains a water sensor or ground sensor, so the "OPTIONAL" part is developed to extend the information found in a query solution but to return the non-optional information anyway. As a result, query water sensor and ground sensor part is set under "SELECT" as
OPTIONAL{
?dhd DHD:hostgroundsettlementsensor ?groundsensor.
For the complete set of query code, check the appendix I.

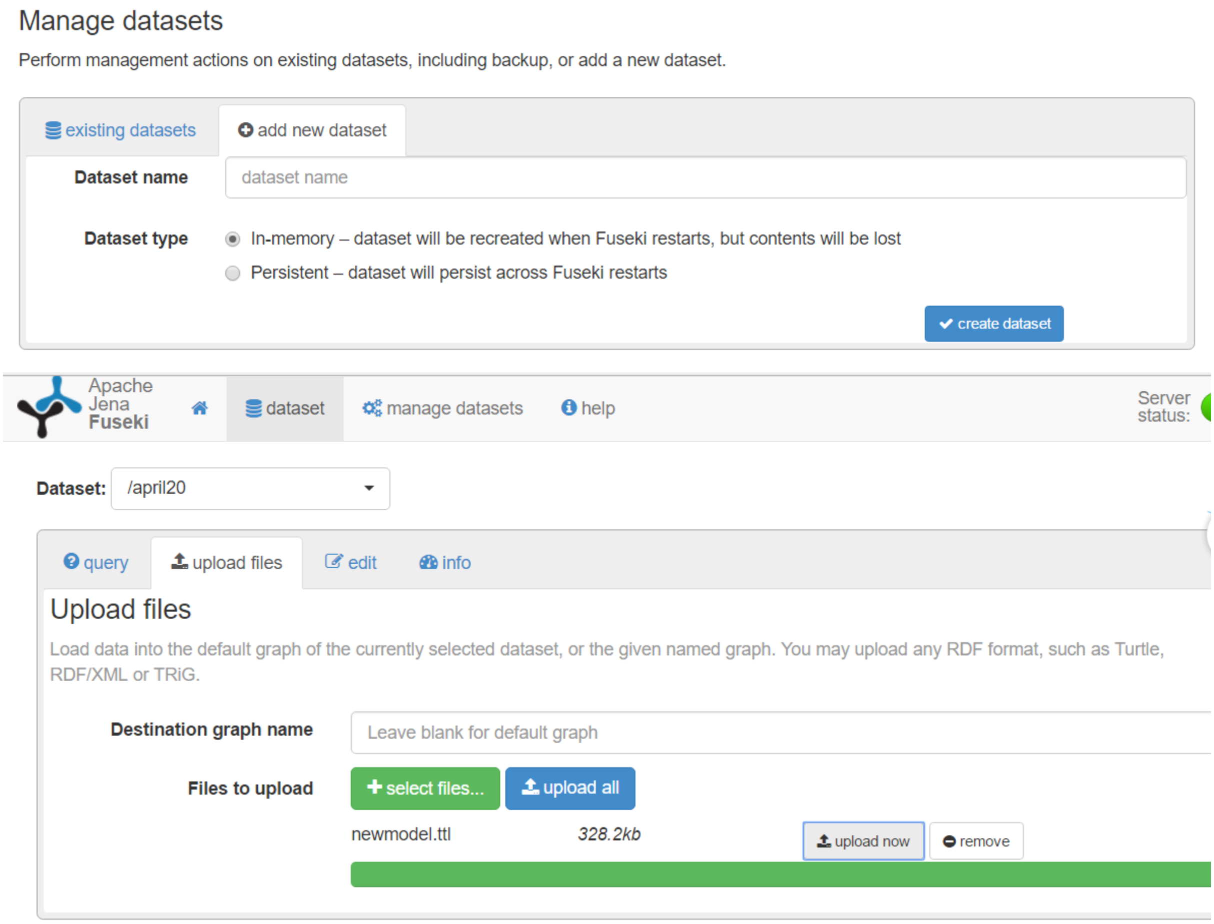


Figure 33 create a dataset in fuseki and then upload it.

The coordinate of drill hole is queried. In which, the location of the drill hole, the code of the drill hole and according accommodate sensors within it are shown. The query code can be referred in appendix I. The part of the query result is shown in Figure 34. And for the complete data please check the appendix.

Table | Raw Response

Showing 1 to 37 of 37 entries

Search: Show 50 entries

| | drillholecode | coordinateX | coordinateY | elevation | groundsensor | watersensor |
|---|---|---|---|---|---|---|
| 1 | "ZK11" | "-3996.25" | "-17292.37" | "6" | | |
| 2 | "ZK6" | "-3137.5" | "-18015.98" | "4.24" | | |
| 3 | "JK8" | "-3209.66" | "-17928.79" | "4.11" | "W8" | "SW8" |

Figure 34 partial query result for designers

The survey point for drill hole is located in lat/lon (39, 54, 57 N; 116, 25, 58 W; 130.049 H), put this coordinates in the coordinates converter, the X= -2180703.61757925, Y= -4386653.2983256. With this survey point, get the global X, Y by simple calculation. The results for drill hole globally coordinate is given in Table 12 below(complete set in appendix J). After getting Global XY for drill holes, converting them back to the lat/lon is the next step. The converters used is the Java code mentioned before, given in the appendix H. The converted lat/lon is given in table 11 below. And the complete table is given in the appendix J.

Table 12 partial Global XY for drill hole

| "DrillHoleCode" | Global X | Global Y |
|---|---|---|
| "JK1" | -2180728.991 | -4386832.946 |
| "JK2" | -2180729.675 | -4386833.526 |

Table 13 partial converted coordinate for drill hole

| "DrillHoleCode" | Global X | Global Y | Lat | Lon |
|---|---|---|---|---|
| "JK1" | -2180728.991 | -4386832.946 | 39 54 54.1184775 N | 116 25 56.3894595 W |
| "JK2" | -2180729.675 | -4386833.526 | 39 54 54.1013389 N | 116 25 56.4043774 W |
| "JK3" | -2180730.319 | -4386835.109 | 39 54 54.0658863 N | 116 25 56.3989889 W |
| "JK4" | -2180732.165 | -4386835.704 | 39 54 54.0377077 N | 116 25 56.4574356 W |

More interestingly, the query so far could help designers to share the existing monitor plan, but on the other hand, offers a possibility to query the drill holes' nearby building elements' location also with SPARQL. To achieve that, the coordinates of building elements required to convert relative value to absolute value first, it is achieved by using IfcOpenShell, because fcOpenShell is an open source (LGPL) software library that helps users and software developers to work with the IFC file format. With the T.F. Krijnen's help, the absolute coordinate value is obtained using Python code (Appendix L). The slabs are taken as examples to trail. After the absolute coordinate value is obtained, it is converted to the latitude and longitude with the converter used in the last part, the latitude and longitude of the slabs are figured. The sorted table recording the slabs information is given in the appendix M. Take drill hole "JK1" as an example, the location of JK1 is shown in Table 13 which is Latitude:39 54 54N and Longitude:116 25 56W. Assume that we would like to know the slabs near the JK1, a rectangular area is planned, one side of this rectangular is from 39 40 00 N to 39 59 00 N, the other side is from 116 20 00W to 116 39 00W. Then we could find out which slab is in this area by using SPARQL query. Since the query content is slightly different, the ”OPTIONAL” is replaced by “filter”. The expected result would be which building element(slab) at what location(within the area). So we set SELECT as “SELECT { ?hasGUID ?hasTAG ?hasLatitude ?hasLongitude” And set WHERE as “WHERE { ?subject BE:hasGUID ?hasGUID.” For complete query code please check appendix I. It turns out there are two elements located within the area, as the query result shows below.

QUERY RESULTS

Table | Raw Response

Showing 1 to 2 of 2 entries — Search: — Show 50 entries

| | hasGUID | hasTAG | hasLatitude | hasLongitude |
|---|---|---|---|---|
| 1 | "0CuGbA85T6COX8m4294VS5" | "477227" | "39 47 4.4868994 N" | "116 35 15.9370863 W" |
| 2 | "2gG5ILN_5FeRcDMsM1xEu" | "648315" | "39 48 38.3500192 N" | "116 35 15.9370863 W" |

Showing 1 to 2 of 2 entries

Figure 35 the query result for building elements near the JK1

**SPARQL query example b**

This query is for a project manager to monitor the current structural properties under the situation that other buildings’ construction operations where these buildings are surrounding the project. To monitor the structural properties in the certain time in case the construction behavior causes the unexpected disturbance. For precautions, better monitoring would be necessary. Here the date is assumed 2016/01/07, the assumption is that in this day, the excavation of surrounding office building’s substructure is conducted. It is quite possible to cause disturbance at this time. The reference block to check the sensing value at the specific day is given in appendix I as well. And the partial query result is shown in the figure below (complete set in appendix j). Moreover, the most potentially infect building structural elements are shown as well. If the sensor data could tell things go wrong, according action would be taken in time.

Table | Raw Response

Showing 1 to 30 of 30 entries — Search: — Show 50 entries

| drillholecode | groundsensor | value_ground | sensingelementground | watersensor | value_water | sensingelementwater |
|---|---|---|---|---|---|---|
| "ZK13" | "W30" | "null" | inst:IfcIdentifier_1954236 | | | |
| "JK17" | "W17" | "null" | inst:IfcIdentifier_1954100 | "SW17" | "-2.196" | inst:IfcIdentifier_778396 |
| "ZK12" | "W29" | "null" | inst:IfcIdentifier_1954219 | | | |
| "JK3" | "W3" | "null" | inst:IfcIdentifier_1954270 | "SW3" | "-3.43" | inst:IfcIdentifier_778304 |

Figure 36 partial query result for project manager

# 6. Conclusion

This thesis introduces an approach to integrate shield tunnel BIM models with geological data using Linked Data after comprehensively studying shield tunnel extension information needs, the IFC standard,and related common extension mechanisms. A case study is conducted to verify the suggested extended BIM model. Based on the whole findings reported in earlier sections, the questions formulated in section would be answered.

**What geological data will be required for shield tunnel BIM models?**

Not only stratum information and groundwater information, but also geological in situ test information and laboratory test information are required for shield tunnel BIM models. For the insitu test, there are 8 items that need to be explored; the laboratory test contains 10 different items, including the geological exploration, there is a total of 22 items as required in the China national Code for Geotechnical Investigation (Code No. GB 50021-2001) to be described so that the shield tunnel related data can be regarded as a full set.

**How to integrate required information within IFC?**

The IfcPropertySet extension can be applied to integrate the required information within Ifc-Shield because compared with the IFC entity extension, the IfcPropertySet extension is more flexible and would not tamper with the IFC model structure, because property sets enable to extend the scope of IFC without changing the schema, a single property as key-value pair that can be attached to nearly any kind of elements and thus enables to extend their attributes.

**What are the common extension mechanisms for BIM model? How do they behave in terms of geological data extension?**

XML, Semantic web, ad hoc heterogeneous data and IfcProxy extension are the most common extension mechanisms for the BIM model. They all have cons and pros, however, in the case of geological data extension for shield tunnel BIM models, based onthe theoretical study, the Linked Data is the desirable mechanism to extend the IFC shield tunnel model. Still, IFC instance modelsare not based on Semantic Web data sets like RDF or OWL data, but on the IFC-SPF. IFC databases can therefore not be directly connected to Semantic Web technology without converting an IFC schema into an OWL ontology. Such linking process is considered to be straightforward except for some minor complications, for instance, once more data sources are involved, the process of RDF conversion needs to be ppeated more oftensince it can not link to IFC directly without converting. Also, for users, learing SPARQL is required even if it is hard to start it. Information in an AEC project is always represented by a specific stakeholder in the building life-cycle. Not only is this stakeholder supposed to be qualified to represent this information, he or she is typically also considered responsible for this information. This is important information that should be taken into account when giving access to the information that is represented by this stakholder, not only for reasons of rights and ownership, but also for reasons of representativeness, trustworthiness and usability. Still, IFC can benefit from the advantages of Semantic Web related technologies due to the possibility of converting IFC into OWL files.

**Which one is the most appropriate approach and how does it work in the actual case?**

As argued in section 3.3.5 and section 4.2, Linked Data approach has been proven to be the most appropriate approach to achieving the goals of extending BIM model. As a verification, a case study of Dongjing metro Station in Shanghai is conducted. By converting the existing geological data related tabular data sets into RDF data sets and linking them with BIM using the ontologies developed . Afterwards, the data can be queried to provide surrounding building designers geo-monitoring related information such as existing sensors' location and monitoring value so that could facilitate the design process.

**Main question: How to extend shield tunnel BIM models with geological data in order to optimize the operation process regarding structural elements of the tunnel and the design process for surrounded buildings?**

In summary, this can be achieved by using a Linked Data approach. A data collection is necessary so to convert the data into RDF (including test result, sensor data etc.) using an ontology designed in the context of this thesis wich meet the requirements . The links can be set to connect the information islands within the merged model to connect the respective data items. In the end, SPARQL is used to query the data.

**Limitation of the thesis**

Though case study proved that RDF is an appropriate approach to extend the shield tunnel model with geological data, there are still limitations regarding this research.

a. Regarding the geological data requirements investigation, the whole requirements analysis is only based on limited tunnel engineering expertise. In different countries, with different backgrounds, they might differ, thus propose some other requirements. To make the property sets more acceptable, the additional, in-depth research is necessary.

b. In the comparison among the extension mechanisms, I concluded, that Linked Data is the most suitable approach in the case of geological data extension. However, it is only based on a literature study and thus only a theoretical conclusion. The extension with the Linked Data is applied in the case study, but other mechanisms are not. It is hard to be sure that the Linked Data approach is the best one.

c. During the research, the large IFC model caused much more troubles than other researchers who have been involved in the Linked Data research. Thus, it can be concluded that once the more complicated data sets are involved, and bigger real-world IFC models are used, the performance of the approach needs to be verified again.

d. Confidentiality issues within the company limited my operation space, data access and a the accuracy of the data result of the case study. On the one hand, it simplified the case, on the other hand, finding from the case study may not be useable in practice.

e. Due to the timeline, the actual visualization of these data query was not completed yet. Since the sensors this thesis studied on are placed out of the building, for the geological data mostly the case, an integration of IfcOpenShell and GIS could be of help.

**Recommendations for further research**

a. As mentioned in the limitations, the data source and size are limited in the case study, thus it is acceptable if the links are created manually. However, the geological data extension required the huge amount of data sources and much bigger BIM model will be involved, then creating links manually seems not to be feasible. In this case, a link generator based on the analysis of RDF model would be more time-saving.

b. Aforementioned visualization issues can be improved for the other researchers, since the geological data tends to be more area-shared, these data may be generated for the specific project, however, from the area development perspective, and the data should be more often reused. Then the visualization fits for not only civil engineers but also urban planners who are responsible for area planning. It is supposed to be designed more user-friendly and conveniently, by e.g. integrating the data with GIS, which could show results within a map..

c. After linking the sensor data with the structural elements, the sensing function works well. But even the sensor indicates the issues; the optimization or precaution measures still need to be done in a separate platform. A system that could integrate the indicators and recommendations platforms based on RDF processing can be a promising product.

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## Appendix A Detailed Geological Required Information List for Shield Tunnel

| | Information item | Explanation |
|---|---|---|
| 1 | Bore hole type | Bore hole type literary description, which is doc. file |
| 2 | Bore hole code | Accordingly code for bore hole, which is supposed to be unique for instance 18XC32 |
| 3 | Drilling method | Drilling method, such as rotary percussion drilling, hammering core drilling, vibratory drilling and etc. |
| 4 | Drilling aims | Drilling purpose based on the drilling method, such as borrow test +standard penetration |
| 5 | Bore hole coordinate X | Port hole coordinate X |
| 6 | Bore hole coordinate Y | Port hole coordinate Y |
| 7 | Elevation of Borehole | Port hole height |
| 8 | Final bore hole depth | Completed hole depth |
| 9 | diameter | Diameter of hole |
| 10 | Deflection of bore hole | Angles of deflection of borehole in different depths, could be multiple angles, which is excel file |
| 11 | Inclinometer depth | The depth of inclinometer point, could be multiple value, correspond to above deflection, which is excel file |
| 12 | Stratigraphic sequence | Within bore hole, top-down sequential number of stratum, start with # 1, which is a excel file |
| 13 | Sequence number code | Code for stratum sequence number, correspond to stratigraphic sequence, which is excel file |
| 14 | Bore hole bottom depth | Measure start from port hole, depth of corresponding stratum floor point, number of items should correspond to stratigraphic sequence, which are all positive values and documented in the excel file. |
| 15 | Sampling rate | The ratio of rock core length from sample and the whole sample length |
| 16 | Stratified soil description | Stratified soil literary description, shown in excel |

| | | |
|---|---|---|
| 17 | Aquifer first appeared water level | Corresponding water level when First time finding water is descripted as elevation |
| 18 | Aquifer stable water level | Corresponding water level when last time finding water is descripted as elevation。 |
| 19 | Number of aquifers | The number of aquifers found during drilling |
| 20 | Aquifer floor depth and floor depth | For phreatic aquifer system, refers to water table, floor depth. For confined water aquifer system, refers to roof and floor depth, correspond to numbers of aquifer, shown in excel file. |
| 21 | Ground water type | Describe revealed ground water type, in literary description, for instance phreatic water, confined water. Correspond to number of aquifers, shown in the excel file. |
| 22 | Ground water quality description | Revealed ground water quality literary description, for instance, causticity. Correspond to number of aquifer, shown in excel file. |
| 23 | Borehole quality | Completed borehole quality in literary description, shown in doc. File or pdf file |
| 24 | Drilling start date | Drilling hole start date. |
| 25 | Complete borehole data | Drilling hole completing date |
| 26 | Construction contractor | Drilling hole construction contractor |
| 27 | File keeper | Drilling hole related information file keeper |
| 28 | Sample information | Certain sample hole information, shown in excel, could be traced through unique code. |
| 29 | Backfilling method | Backfilling method literary description |
| 30 | Backfilling material | Backfilling material literary description |
| 31 | Import standard | All the cited standards during the drilling process (URL link), shown in excel. |

Appendix table 1 geological investigation required information list

| | Information item | Explanation |
|---|---|---|
| 1 | code | Observation well code, supposed to unique |
| 2 | Coordinate X | Well head coordinate X |
| 3 | Coordinate Y | Well head coordinate Y |
| 4 | Wellhead | Wellhead elevation |

| | | |
|---|---|---|
| | elevation | |
| 5 | location | Location literary description |
| 6 | Depth of well | Depth of well |
| 7 | Causticity description | Evaluation of ground water causticity |
| 8 | Water level | Each time, the observed water level, shown in excel |
| 9 | Observation date | Observation date of each time, shown in excel |
| 10 | Import standard | All the cited standards during the observation process (URL link), shown in excel. |

Appendix table 2 Required ground water observation well information list

| | Information item | Explanation |
|---|---|---|
| 1 | Sourced bore hole code | The borehole code of sample |
| 2 | Sampled hole Stratigraphic sequence | Stratigraphic sequence within sample from bore hole, start from 1. |
| 3 | Sample roof depth | The depth from roof to porthole when sampling |
| 4 | Sample floor depth | The depth from floor to porthole when sampling |
| 5 | Degree of disturbance | The degree of disturbance when sampling description in literary, for instance, undisturbed |
| 6 | Sampling method | Sampling method in literary description |
| 7 | Experiment content | The aimed experiment item of sampling, such as density, soil naming and etc. |
| 8 | Sampling date | Sate of sampling, and time of it |
| 9 | Stratum code | The stratum code of sourced sample |
| 10 | Sampling operator | Name of sampling operator |
| 11 | Sample information | The laboratory test sample code which sample is taken from borehole, the code is supposed to be unique in the project, listed in the excel |
| 12 | Imported standard | All the cited standards during the sampling (URL link), shown in excel. |

Appendix table 3 required sampling information list

| | Information item | Explanatory |
|---|---|---|

| | | |
|---|---|---|
| 1 | Geological formation name | Geological formation name such as: artificial earth fill, clay silt and etc. |
| 2 | Stratigraphic sequence | top-down sequential number of stratum, start with # 1, which is a excel file |
| 3 | Sequence number code | Code for stratum sequence number, correspond to stratigraphic sequence, which is excel file |
| 4 | Geological time | Geological time description |
| 5 | Compactness description | Stratum compactness description such as loose, compacting and etc. |
| 6 | Cause type | The type of stratum cause in literary description, such as marina -estuary。 |
| 7 | Stratigraphic floor depth range | The depth range of certain stratigraphic floor |
| 8 | Stratigraphic floor elevation range | The elevation range of certain stratigraphic floor |
| 9 | Stratigraphic thickness range | The thickness range of certain stratigraphic layer |
| 10 | Average thickness | Average stratigraphic thickness |
| 11 | Surrounding rock classification | Stratum surrounding rock classification |
| 12 | dredgeability | Grades of dredgeability, such as loosening soil, pan formation and etc. |
| 13 | Soil property description | Literary description of soil property |

Appendix table 4 required stratigraphic information list

| | Information index | Explanatory |
|---|---|---|
| 1 | Natural moisture content | Natural moisture, showed in percentage |
| 2 | Bulk density | Soil bulk density |
| 3 | Dry density | Soil dry density |
| 4 | Particle density | Soil particle density |
| 5 | Natural density | Soil natural density |
| 6 | Grain density | Soil grain density |
| 7 | Saturation level | Soil saturation level |
| 8 | Porosity | Soil porosity |
| 9 | Coefficient of homogeneity | Particle coefficient of homogeneity |
| 10 | Liquid limit | Liquid limit of soil |
| 11 | Plastic limit | Plastic limit of soil |
| 12 | plastic index | soil plastic limit index |
| 13 | Liquid index | Soil plastic index |
| 14 | Horizontal foundation coefficient | Horizontal foundation coefficient |

| | | |
|---|---|---|
| 15 | Vertical foundation coefficient | Vertical foundation coefficient |
| 16 | Vertical permeability coefficient | Vertical permeability coefficient |
| 17 | Horizontal permeability coefficient | Horizontal permeability coefficient |
| 18 | cohesion of fast triaxial shear | The strength parameter of unconsolidated-undrained triaxial test: cohesion |
| 19 | Angle of internal friction of fast triaxial shear | The strength parameter of unconsolidated-undrained triaxial test: The angle of internal friction |
| 20 | Consolidated quick triaxial shear effective cohesion | The strength parameter of consolidated-undrained triaxial test: effective cohesion |
| 21 | Consolidated quick triaxial shear effective angle of internal friction | The strength parameter of consolidated-undrained triaxial test: effective angle of internal friction |
| 22 | Consolidated-drained quick triaxial shear cohesion | The strength parameter of Consolidated-drained triaxial test: cohesion |
| 23 | Consolidated-drained quick triaxial shear angle of internal friction | The strength parameter of Consolidated-drained triaxial test: angle of internal friction |
| 24 | Consolidated quick shear cohesion (peak) | Cohesion Peak value during Consolidated quick shear test |
| 25 | Consolidated quick shear angle of internal friction (peak) | Angle of internal friction Peak value during Consolidated quick shear test |
| 26 | Direct quick shear test cohesion (peak) | Cohesion peak value during Direct quick shear test |
| 27 | Direct quick shear test angle of internal friction (peak) | Angle of internal friction peak value during Direct quick shear test |
| 28 | Unconfined compression strength （undisturbed soil） | Unconfined compression strength （undisturbed soil） |
| 29 | Unconfined compression strength （manipulated soil） | Unconfined compression strength （manipulated soil） |
| 30 | Sensitivity | Soil sensitivity |
| 31 | Compressibility index | Soil Compressibility index |
| 32 | Coefficient f compressibility | Soil Coefficient compressibility |
| 33 | Compression modulus | Soil Compression modulus |

| | | |
|---|---|---|
| 34 | Chord modulus | Soil chord modulus |
| 35 | Rebound index | Soil Rebound index |
| 36 | Deformation modulus | Soil deformation modulus |
| 37 | Lateral earth pressure coefficient at rest | Soil Lateral earth pressure coefficient at rest |
| 38 | preconsolidation pressure | Soil preconsolidation pressure |

Appendix table 5 major stratum physical and mechanical feature index information

| | |
|---|---|
| Test range description | |
| hole code | |
| Test location elevation | |
| Standard penetration times | |
| Penetrated strati graphic code | |
| Average penetrated times | |
| Test evaluation | |

Appendix table 6 standard penetration test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel。 |

Appendix table 7 other required information list in the standard penetration test

| | |
|---|---|
| Test range description | |
| hole code | |
| Test location elevation | |
| Standard penetration times | |
| Penetrated strati graphic code | |
| Average penetrated times | |
| Test evaluation | |

Appendix table 8 cone penetration test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 9 other necessary information list for cone penetration test

| Information item | Content |
|---|---|
| Equipment type | |
| Borehole code | |
| Test spot elevation | |
| Stratigraphic code(m) | |
| Starting pressure(KPa) | |
| Extreme pressure(kPa) | |
| Critical edge pressure(kPa) | |
| Critical Load of Soil Mass(kPa) | |
| Ultimate Load of Soil Mass(kPa) | |
| Critical edge strength(kPa) | |
| Pressuremeter shear modulus(kPa | |
| Pressuremeter modulus(kPa) | |
| Young’s modulus(MPa) | |
| Empirical formula compression modulus(MPa) | |
| Deformation modulus(MPa) | |
| Test evaluation | |

Appendix table 10 lateral loading test required information list

| | Information | Explanatory |
|---|---|---|

| | item | |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 11 the other required information in the lateral loading test

| Information item | content |
|---|---|
| Test site description | |
| Borehole code | |
| Stratigraphic code | |
| Pressurized type | |
| Detector type | |
| Penetration type(m) | |
| Detector resistance(KPa) | |
| Specific penetration resistance(KPa) | |
| Side friction(KPa) | |
| Frictional resistance ratio(%) | |
| pore water pressure(KPa) | |
| Soil type | |
| Estimated horizontal consolidation coefficient (cm2/s) | |
| Estimated undrained shear strength(KPa) | |
| Estimated sand internal angle of friction(°) | |
| Estimated sand compression modulus(MPa) | |
| Estimated clay compression modulus(MPa) | |
| Estimated clay deformation modulus(MPa) | |
| Test evaluation | |

Appendix table 12 static penetration test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 13 the other required information in the static penetration test

| Information item | explanatory |
|---|---|
| Test site description | |
| Borehole code | |
| Stratigraphic code | |
| Test type | |
| Loading bearing plate | |
| Diameter or width of loading bearing plate | |
| Loading type | |
| Loading level (KN) | |
| Settlement (mm) | |
| Duration (min) | |
| Foundation bearing capability eigen value (KPa) | |
| Deformation modulus (KPa) | |
| coefficient of subgrade reaction(kN/m3) | |
| Amended coefficient of subgrade reaction (KN/m3) | |
| Horizontal consolidation coefficient (cm2/s) | |
| Test evaluation | |

Appendix table 14 static loading test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 15 the other required information in the static loading test

| Information item | |
|---|---|
| Test site description | |
| Borehole code | |
| Stratigraphic code | |
| Test spot depth | |
| Horizontal stress index | |
| Dilatational modulus | |
| Lateral earth pressure coefficient at rest | |
| Undrained shear strength | |
| Horizontal coefficient of subgrade | |
| Horizontal consolidation coefficient | |
| Compression modulus | |
| Test evaluation | |

Appendix table 16 flat dilatometer test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |

| | | |
|---|---|---|
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 17 the other required information in the flat dilatometer test

| Information item | Explanatory |
|---|---|
| Test site description | |
| Borehole code | |
| Stratigraphic code | |
| Test spot depth | |
| Test type | |
| Undisturbed soil shear strength | |
| Amended Undisturbed soil shear strength | |
| Manipulated soil shear strength | |
| Amended Manipulated soil shear strength | |
| Sensitivity | |
| Test evaluation | |

Appendix table 18 vane shear test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 19 the other required information in the vane shear test

| Information item | Explanatory |
|---|---|
| Test site description | |
| Borehole code | |
| Stratigraphic code | |
| Test spot depth | |
| Test type | |
| Shear plane description | |
| Normal load | |
| Normal stress | |
| Cutting stress | |
| Cutting deformation | |
| Peak shear strength | |
| Remained shear strength | |
| Vertical deformation | |
| Dilatancy strength | |
| Destructive shape on the shear plane | |
| Test evaluation | |

Appendix table 20 in situ direct test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 21 the other required information in the in situ shear test

| | |
|---|---|
| Sample code | |
| Cutting ring code | |
| Soil mass (g) | |

| | |
|---|---|
| Volume (cm3) | |
| Wet soil density (g/cm3) | |
| Moisture content (%) | |
| Dry density (g/cm3) | |
| Average dry density (g/cm3) | |

Appendix table 22 cutting ring method required information list

| | |
|---|---|
| Sample code | |
| Sample Mass (g) | |
| Wax- sealed sample mass (g) | |
| Wax- sealed sample water mass (g) | |
| Water temperature (℃) | |
| Density of wax (g/cm3) | |
| Wax volume (cm3) | |
| Wax sealing sample volume (cm3) | |
| Sample Volume (cm3) | |
| moisture density (g/cm3) | |
| Moisture content (%) | |
| Dry density (g/cm3) | |
| Average dry density (g/cm3) | |

Appendix table 23 wax sealed method required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 24 the other required information in the in density test

| | |
|---|---|
| Aperture (mm) | |
| The mass of retained soil (g) | |
| Cumulative mass of retained soil (g) | |
| The mass of the soil particles whose size is less than the aperture(g) | |
| The percentage of the soil particles whose size is less than the aperture (%) | |

Appendix table 25 sieving test required information list

| | |
|---|---|
| dropping time(min) | |
| Suspension temperature(℃) | |
| Soil particles drop-distance(cm) | |
| The percentage of the smaller soil particles (%) | |
| The entire percentage of the smaller soil particles (%) | |

Appendix table 26 densitometer required information list

| | | |
|---|---|---|
| 1 | Project name | The corresponding project's name. |
| 2 | Borehole code | Production samples of the soil belongs to drill number. |
| 3 | Soil description | Description of the sample. |
| 4 | Test description | Brief textual description of the experiment's scheme. |
| 5 | Test dates | Test time. |
| 6 | Test operator | The name of the experimental personnel. |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |
| 11 | Controlled particle size | d 60 : The particle size whose cumulative Percentage is 60% (mm). |
| 12 | Middle size | d 50 : The particle size whose cumulative Percentage is 50% (mm). |
| 13 | Effective size | d 10 : The particle size whose cumulative Percentage is 10% (mm). |
| 14 | Inhomogeneous coefficient (Cu) | Uniformity coefficient of graded index:d60/ d 10 。 |
| 1 | Curvature | Curvature coefficient of graded |

| | | |
|---|---|---|
| 15 | coefficient(Cc) | index:(d30*d30)/(d60*d10)。 |
| 16 | Soil sample named | Name the soil according to the classification criteria. |

Appendix table 27 list of other required information in the grain size test

| | |
|---|---|
| Sample Control number | |
| Soil samples Introductions | |
| Box Number | |
| Box mass (g) | |
| The mass of the box and the wet soil (g) | |
| The mass of the box and the dry soil (g) | |
| Water Mass (g) | |
| Dry soil Mass (g) | |
| Moisture content (%) | |
| Average moisture content (%) | |

Appendix table 28 moisture content test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 29 other needed information for moisture content test

| | |
|---|---|
| Sample number | |
| Tapered sinking depth (mm) | |
| Box Number | |
| Box mass (g) | |
| The mass of the box and the wet soil (g) | |
| The mass of the box and the dry soil (g) | |
| Water Mass (g) | |

| | |
|---|---|
| Dry soil Mass (g) | |
| Moisture content (%) | |
| Liquid limit (%) | |
| Plastic limit (%) | |

Appendix table 30 atterberg limit test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 31 other required information in the atterberg limits test

| | |
|---|---|
| Instrument code | |
| Sample code | |
| Dynamometer calibration coefficients (kPa/0.01mm) | |
| Test method | |
| Handwheel speed ( go/min) | |
| Vertical pressure(kPa) | |
| Dynamometer's reading(0.01mm) | |
| The shear strength of Specimens (kPa) | |
| The angle of internal friction(°) | |
| Cohesion(kPa) | |

Appendix table 32 direct shear test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |

| | | |
|---|---|---|
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 33 other needed information in the direct shear test

| | |
|---|---|
| Sample Control code | |
| Test type | |
| Pressure(kPa) | |
| The axis strain at destruction | |
| The major axis stress at destruction(kPa) | |
| Water pressure in pore at destruction(kPa) | |
| The effective major axis stress at destruction (kPa) | |
| The effective minor axis stress at destruction (kPa) | |
| The ratio for valid primary Stress | |
| Damage description | |

Appendix table 34 traxial compression test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |

| | | |
|---|---|---|
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 35 other needed information in the traxial compression test

| | |
|---|---|
| Sample code | |
| Test type | |
| Initial pore ratio (%) | |
| Stress levels(kPa) | |
| Stable consolidation void ratio under pressure at various levels (%) | |
| Compression coefficient under pressure at various levels (kPa-1) | |
| The internal compression modulus under pressure at various levels (MPa) | |
| The coefficient of volume compressibility under pressure at various levels (MPa-1) | |
| The preconsolidation pressure (kPa) | |
| The compression index under pressure at various levels (kPa-1) | |
| Rebound index levels of pressure range(kPa-1) | |
| Consolidation coefficient(cm2/s) | |
| Solution method of consolidation coefficient | |

Appendix table 36 consolidation test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test | Name of test contractor |

| | | |
|---|---|---|
| | contractor | |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 37 general needed information for the consolidation test

| Sample number | Test method | Axial effective stress(kPa) | Lateral effective stress (kPa) | Lateral earth pressure coefficient |
|---|---|---|---|---|
| | | | | |

Appendix table 38 static lateral stress coefficient test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 39 other general information needed in the static lateral stress test

| | |
|---|---|
| Sample number | |
| Undisturbed soil strain | |
| Undisturbed axial stress (kPa) | |
| Undisturbed sample failure mode | |
| Manipulated soil axial strain | |
| Manipulated soil axial stress(kPa) | |
| Manipulated soil failure modes | |
| Unconfined compressive strength of undisturbed sample (kPa） | |
| Unconfined compressive strength of remoulded specimens (kPa) | |

| | |
|---|---|
| Sensitivity | |

Appendix table 40 unconfined compression strength test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 41 other general information needed in the unconfined compression strength test

| Sample number | Test type | Test serial number | Water temperature | Penetration direction | Permeability coefficient After correction (cm/s) | Average permeability coefficient(cm/s) |
|---|---|---|---|---|---|---|
| | | | | | | |

Appendix table 42 permeability test required information list

| | Information item | Explanatory |
|---|---|---|
| 1 | Project name | Corresponding project name |
| 2 | Borehole code | The code of sourced borehole |
| 3 | Soil description | Sample soil description |
| 4 | Test description | Brief literary description of test |
| 5 | Test date | Test date |
| 6 | Test operator | Name of test operator |
| 7 | Data analyst | Name of data analyst |
| 8 | Collator | Name of collator |

| | | |
|---|---|---|
| 9 | Test contractor | Name of test contractor |
| 10 | Imported standard | All the cited standards (URL link), shown in excel. |

Appendix table 43 other general information needed in the permeability test

# Appendix B Geological survey information property set

Borehole and stratum information property set

(1)Borehole information property set

| **Property Set Name** | Pset_BoreholeCommon | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcBorehole** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Borehole general property information | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| DrillingType | IfcPropertySingleValue | IfcLabel | - | DrillingType |
| DrillingCode | IfcPropertySingleValue | IfcLabel | - | DrillingCode |
| DrillingMethod | IfcPropertySingleValue | IfcLabel | - | DrillingMethod |
| DrillingPurpose | IfcPropertySingleValue | IfcLabel | - | DrillingPurpose |
| CoordinateX | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | Porthole coordinate X |
| CoordinateY | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | Porthole coordinate Y |
| TopElevation | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | TopElevation |
| Depth | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | Depth |
| Diameter | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | Diameter |
| DeflexionAngle | IfcPropertyListValue | IfcPlaneAngleMeasure | PLANEANGLEUNIT | DeflexionAngle |
| DeflexionDepth | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | DeflexionDepth |

| | | | | |
|---|---|---|---|---|
| StratumSequenceNumbe r | IfcPropertyListValue | IfcInteger | - | StratumSequenceNumber |
| StratumCode | IfcPropertyListValue | IfcLabel | - | StratumCode |
| SegmentBottomDepth | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | SegmentBottomDepth |
| SamplingRate | IfcPropertyListValue | IfcRatioMeasure | - | SamplingRate |
| SoilDescription | IfcPropertyListValue | IfcLabel | - | SoilDescription |
| AquiferTopLevel | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | the level of aquifer when it is first time found |
| AquiferStableLevel | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | the level of aquifer when it is stable |
| AquiferCount | IfcPropertySingleValue | IfcInteger | - | The number of aquifers |
| AquiferDepthRange | IfcComplexProperty /IfcPropertyBoundedValue | IfcLengthMeasure | LENGTHUNIT | Depth range of aquifer |
| GroundWaterType | IfcPropertySingleValue | IfcLabel | - | GroundWaterType |
| GroundWaterDescriptio n | IfcPropertySingleValue | IfcLabel | - | Ground Water Description |
| FinishQuality | IfcPropertyListValue | IfcIdentifier | - | The quality of finished hole |
| StartDateTime | IfcPropertySingleValue | IfcDateTime | - | Start Date Time |
| FinishDateTime | IfcPropertySingleValue | IfcDateTime | - | Finish Date Time |
| ConstructionUnit | IfcPropertySingleValue | IfcLabel | - | Construction Unit |
| DataKeepUnit | IfcPropertySingleValue | IfcLabel | - | Data Keep Unit |
| SoilSamples | IfcPropertyListValue | IfcIdentifier | - | Soil Samples |
| BackfillMethod | IfcPropertySingleValue | IfcLabel | - | Back fill Method |
| BackMaterial | IfcPropertySingleValue | IfcLabel | - | Back fill Material |

| | | | | |
|---|---|---|---|---|
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | Referenced Specifications |

⑵ Water observation well property set

| **Property Set Name** | Pset_WaterObservationWellCommon | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcWaterObservationWell** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Water observation well general property information | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| WellCode | IfcPropertySingleValue | IfcLabel | - | WellCode |
| CoordinateX | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | CoordinateX |
| CoordinateY | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | CoordinateY |
| TopElevation | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | Porthole elevation |
| LocationDescription | IfcPropertySingleValue | IfcLabel | - | Location literary Description |
| TotalLength | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | Total Length |
| CorrosionDescription | IfcPropertySingleValue | IfcLabel | - | Corrosion Description |
| WaterLevel | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | Water Level |
| ObservationTime | IfcPropertyListValue | IfcDateTime | - | Observation Time |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | Referenced Specifications |

⑶Borehole sample information

| **Property Set Name** | Pset_BoreholeSoilSampleCommon |
|---|---|

| Applicable Entities | IfcSoilSample | | | |
|---|---|---|---|---|
| Applicable Type Value | | | | |
| Definition | Borehole sample general information | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| BoreholeCode | IfcPropertySingleValue | IfcLabel | - | Code of sourced borehole |
| SequenceInBorehole | IfcPropertySingleValue | IfcInteger | - | SequenceInBorehole |
| DepthToTopOfSample | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | DepthToTopOfSample |
| DepthToBottomOfSample | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | DepthToBottomOfSample |
| StateDecription | IfcPropertySingleValue | IfcLabel | - | Disturbed State Decription |
| SamplingMethod | IfcPropertySingleValue | IfcLabel | - | SamplingMethod |
| DepthToGroundWater | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | DepthToGroundWater |
| ReasonForSampling | IfcPropertySingleValue | IfcLabel | - | ReasonForSampling |
| Time | IfcPropertySingleValue | IfcDateTime | - | Time |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |
| PersonName | IfcPropertySingleValue | IfcLabel | - | PersonName |
| Specimens | IfcPropertyListValue | IfcIdentifier | - | Specimens |
| ReferencedSpecifications | IfcComplexProperty<br>/IfcPropertyReferenceValue | | - | ReferencedSpecifications |

(4)Stratigraphic distribution information property set

| Property Set Name | Pset_StratumCommon |
|---|---|
| **Applicable Entities** | **IfcStratum** |

| Applicable Type Value | | | | |
|---|---|---|---|---|
| **Definition** | Stratum information description | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |
| SetratumSequenceNumber | IfcPropertySingleValue | IfcInteger | | SetratumSequenceNumber |
| GeologyAge | IfcPropertySingleValue | IfcLabel | - | GeologyAge |
| CompactDescription | IfcPropertySingleValue | IfcLabel | - | CompactDescription |
| FormationType | IfcPropertySingleValue | IfcLabel | - | FormationType |
| LayerBottomDepth | IfcPropertyBoundedValue | IfcLengthMeasure | LENGTHMEASUREUNIT | LayerBottomDepth |
| LayerBottomElevation | IfcPropertyBoundedValue | IfcLengthMeasure | LENGTHMEASUREUNIT | LayerBottomElevation |
| Thickness | IfcPropertyBoundedValue | IfcLengthMeasure | LENGTHMEASUREUNIT | Thickness |
| AverageThickness | IfcPropertySingleValue | IfcLengthMeasure | LENGTHMEASUREUNIT | AverageThickness |
| RockClassification | IfcPropertySingleValue | IfcLabel | - | RockClassification |
| ExcavationClassification | IfcPropertySingleValue | IfcLabel | - | ExcavationClassification |
| SoilBehaviorDescription | IfcPropertySingleValue | IfcText | - | SoilBehaviorDescription |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

(5) Stratum physical-mechanical index

| Property Set Name | Pset_StratumSoilProperties | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcStratum** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Stratum physical-mechanical index | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| MoistureContent | IfcPropertySingleValue | IfcReal | - | MoistureContent |
| BulkDensity | IfcPropertySingleValue | IfcMassDensityMeasure | MASSDENSITYUNIT | BulkDensity |
| DryDensity | IfcPropertySingleValue | IfcMassDensityMeasure | MASSDENSITYUNIT | DryDensity |
| ParticleDensity | IfcPropertySingleValue | IfcMassDensityMeasure | MASSDENSITYUNIT | ParticleDensity |
| NaturalUnitWeight | IfcPropertySingleValue | IfcMassDensityMeasure | MASSDENSITYUNIT | NaturalUnitWeight |
| SpecificGravity | IfcPropertySingleValue | IfcReal | - | SpecificGravity |
| DegreeOfSaturation | IfcPropertySingleValue | IfcReal | - | DegreeOfSaturation |
| VoidsRatio | IfcPropertySingleValue | IfcReal | - | VoidsRatio |
| CofficientOfUniformity | IfcPropertySingleValue | IfcReal | - | CofficientOfUniformity |
| LiquidLimit | IfcPropertySingleValue | IfcReal | - | LiquidLimit |
| PlasticLimit | IfcPropertySingleValue | IfcReal | - | PlasticLimit |
| PlasticityIndex | IfcPropertySingleValue | IfcReal | - | PlasticityIndex |
| LiquidityIndex | IfcPropertySingleValue | IfcReal | - | LiquidityIndex |
| HorizontalCofficientOfSubgradeRea | IfcPropertySingleValue | IfcMassDensityMeasure | MASSDENSITYUNI | HorizontalCofficien |

| | | | | |
|---|---|---|---|---|
| ction | | | T | tOfSubgradeReaction |
| VerticalCofficientOfSubgradeReaction | IfcPropertySingleValue | IfcMassDensityMeasure | MASSDENSITYUNIT | VerticalCofficientOfSubgradeReaction |
| VerticalCofficientOfPermeability | IfcPropertySingleValue | IfcLinearVelocityMeasure | LINEARVELOCITYUNIT | VerticalCofficientOfPermeability |
| HorizontalCofficientOfPermeability | IfcPropertySingleValue | IfcLinearVelocityMeasure | LINEARVELOCITYUNIT | HorizontalCofficientOfPermeability |
| CohensionOfTriaxialQuickShearTest(UU) | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | CohensionOfTriaxialQuickShearTest(UU) |
| FrictionAngleOfTriaxialQuickShearTest(UU) | IfcPropertySingleValue | IfcPlaneAngleMeasure | PLANEANGLEUNIT | FrictionAngleOfTriaxialQuickShearTest(UU) |
| CohensionOfTriaxialConsolidatedQuickShearTest(CU) | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | CohensionOfTriaxialConsolidatedQuickShearTest(CU) |
| FrictionAngleOfTriaxialConsodilatedQuickShearTest(CU) | IfcPropertySingleValue | IfcPlaneAngleMeasure | PLANEANGLEUNIT | FrictionAngleOfTriaxialConsodilatedQuickShearTest(CU) |
| EffectiveCohensionOfTriaxialConsolidatedQuickShearTest(CU) | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | EffectiveCohensionOfTriaxialConsolidatedQuickShearTest(CU) |
| EffectiveFrictionAngleOfTriaxialConsodilatedQuickShearTest(CU) | IfcPropertySingleValue | IfcPlaneAngleMeasure | PLANEANGLEUNIT | EffectiveFrictionAngleOfTriaxialConsodilatedQuickShearTest(CU) |

| | | | | |
|---|---|---|---|---|
| CohensionOfTriaxialConsolidatedAndDrainShearTest(CD) | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | CohensionOfTriaxialConsolidatedAndDrainShearTest(CD) |
| FrictionAngleOfTriaxialConsodilatedAndDrainShearTest(CD) | IfcPropertySingleValue | IfcPlaneAngleMeasure | PLANEANGLEUNIT | FrictionAngleOfTriaxialConsodilatedAndDrainShearTest(CD) |
| CohensionOfConsolidatedQuickShearTest(Peak) | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | CohensionOfConsolidatedQuickShearTest(Peak) |
| FrictionAngleOfConsolidatedQuickShearTest(Peak) | IfcPropertySingleValue | IfcPlaneAngleMeasure | PLANEANGLEUNIT | FrictionAngleOfConsolidatedQuickShearTest(Peak) |
| CohensionOfDirectQuickShearTest(Peak) | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | CohensionOfDirectQuickShearTest(Peak) |
| FrictionAngleOfDirectQuickShearTest(Peak) | IfcPropertySingleValue | IfcPlaneAngleMeasure | PLANEANGLEUNIT | FrictionAngleOfDirectQuickShearTest(Peak) |
| UnconfinedCompressiveStrength(UndisturbedSoil) | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | UnconfinedCompressiveStrength(UndisturbedSoil) |
| UnconfinedCompressiveStrength(RemoldedSoil) | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | UnconfinedCompressiveStrength(RemoldedSoil) |
| Sensibility | IfcPropertySingleValue | IfcReal | - | Sensibility |
| CompressonIndex | IfcPropertySingleValue | IfcReal | - | CompressonIndex |

| | | | | |
|---|---|---|---|---|
| CofficientOfCompressibility | IfcPropertySingleValue | IfcReal | USEDEFINED | CofficientOfCompressibility |
| CompressionModulus | IfcPropertySingleValue | IfcShearModulusMeasure | MODULUSOFELASTICITYUNIT | CompressionModulus |
| ElasticModulus | IfcPropertySingleValue | IfcModulusOfElasticityMeasure | MODULUSUNITOFELASTICITYUNIT | ElasticModulus |
| SwellingIndex | IfcPropertySingleValue | IfcReal | - | SwellingIndex |
| DeformationModulus | IfcPropertySingleValue | IfcModulusOfElasticityMeasure | SHEARMODULUSUNI | DeformationModulus |
| LateralPressureCofficientAtRest | IfcPropertySingleValue | IfcReal | - | LateralPressureCofficientAtRest |
| PreConsolidationPressure | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | PreConsolidationPressure |

## Laboratory test information property set

(1)Density test with cutting ring method

| | |
|---|---|
| **Property Set Name** | Pset_SoilSpecimenDensityTestByCuttingRingMethodResult |
| **Applicable Entities** | **IfcSoilSpecimen** |

| **Applicable Type Value** | | | | |
|---|---|---|---|---|
| **Definition** | Result information of a set of density test with cutting ring method sample | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| ProjectName | IfcPropertySingleValue | IfcLabel | – | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | – | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | – | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | – | ProcedureDescription |
| RingKnifeCode | IfcPropertyListValue | IfcLabel | – | RingKnifeCode |
| WetSoilQuality | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | WetSoilQuality |
| DrySoilQuality | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | DrySoilQuality |
| SoilVolume | IfcPropertyListValue | IfcVolumeMeasure | VOLUMEUNIT | SoilVolume |
| WetDensity | IfcPropertyListValue | IfcMassDensityMeasure | MASSDENSITYUNIT | WetDensity |
| DryDensity | IfcPropertyListValue | IfcMassDensityMeasure | MASSDENSITYUNIT | DryDensity |
| AverageDryDensity | IfcPropertySingleValue | IfcMassDensityMeasure | MASSDENSITYUNIT | AverageDryDensity |
| SoilDescription | IfcPropertyListValue | IfcLabel | – | SoilDescription |
| TestTime | IfcPropertyListValue | IfcDateTime | – | TestTime |
| ExperimentorName | IfcPropertyListValue | IfcLabel | – | ExperimentorName |
| CheckerName | IfcPropertyListValue | IfcLabel | – | CheckerName |
| CalculatorName | IfcPropertyListValue | IfcLabel | – | CalculatorName |
| TestUnit | IfcPropertyListValue | IfcLabel | – | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | – | ReferencedSpecifications |

⑵Density test with wax sealing method

| **Property Set Name** | Pset_SoilSpecimenDensityTestByWaxSealingMethodResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcSoilSpecimen** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Result information of a set of density test with wax sealing method sample | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | - | ProcedureDescription |
| SpecimenCode | IfcPropertyListValue | IfcLabel | - | SpecimenCode |
| MassWithoutWax | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassWithoutWax |
| MassWithWax | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassWithWax |
| MassWithWaxInWater | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassWithWaxInWater |
| WaterTemperature | IfcPropertyListValue | IfcThermodynamicTemperatureMeasure | THERMODYNAMICTEMPERATUREUNIT | WaterTemperature |
| Water'sDensity | IfcPropertyListValue | IfcMassDensityMeasure | MASSDENSITYUNIT | Water'sDensity |
| Wax'sDensity | IfcPropertyListValue | IfcMassDensityMeasure | MASSDENSITYUNIT | Wax'sDensity |
| VolumeOfSpecimenWithWax | IfcPropertyListValue | IfcVolumeMeasure | VOLUMEUNIT | VolumeOfSpecimenWithWax |
| VolumeOfWax | IfcPropertyListValue | IfcVolumeMeasure | VOLUMEUNIT | VolumeOfWax |

| | | | | |
|---|---|---|---|---|
| VolumeOfSpecimenWithout Wax | IfcPropertyListValue | IfcVolumeMeasure | VOLUMEUNIT | VolumeOfSpecimenWit houtWax |
| WetDensity | IfcPropertyListValue | IfcMassDensityMeasur e | MASSDENSITYUNIT | WetDensity |
| MoistureContent | IfcPropertyListValue | IfcReal | - | MoistureContent |
| DryDensity | IfcPropertyListValue | IfcMassDensityMeasur e | MASSDENSITYUNIT | DryDensity |
| AverageDensity | IfcPropertyListValue | IfcMassDensityMeasur e | MASSDENSITYUNIT | AverageDensity |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| Tester | IfcPropertyListValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertyListValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertyListValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceVa lue | | - | ReferencedSpecificatio ns |

(3) Particle analysis test by sieve method

| | |
|---|---|
| **Property Set Name** | Pset_SoilSpecimenParticleAnalysisTestBySieveMethodResult |
| **Applicable Entities** | **IfcSoilSpecimen** |
| **Applicable Type Value** | |
| **Definition** | Result information of particle analysis test by sieve method |

| Property Name | Property Type | Data Type | Unit | Definition |
|---|---|---|---|---|
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | - | ProcedureDescription |
| SpecimenCode | IfcPropertyListValue | IfcLabel | - | SpecimenCode |
| Diameter | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | Diameter |
| MassOfRetainedSoil | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassOfRetainedSoil |
| AccumulatedQMassOfRetainedSoil | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | AccumulatedQMassOfRetainedSoil |
| MassOfSoilLessThanDiameter | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassOfSoilLessThanDiameter |
| MassPercentOfSoilLessThanDiameter | IfcPropertyListValue | IfcRatioMeasure | - | MassPercentOfSoilLessThanDiameter |
| ConstrainedGrainSize | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | ConstrainedGrainSize |
| AverageGrainSize | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | AverageGrainSize |
| EffectiveGrainSize | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | EffectiveGrainSize |
| CofficientOfNonuniformity | IfcPropertySingleValue | IfcReal | - | CofficientOfNonuniformity |
| CofficientOfGraduation | IfcPropertySingleValue | IfcReal | - | CofficientOfGraduation |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |

| | | | | |
|---|---|---|---|---|
| Tester | IfcPropertyListValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertyListValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertyListValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

⑷Particle analysis test with densimeter method

| **Property Set Name** | Pset_SoilSpecimenParticleAnalysisTestByDensimeterMethodResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcSoilSpecimen** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Result information of particle analysis test by densimeter method | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | - | ProcedureDescription |
| SpecimenCode | IfcPropertyListValue | IfcLabel | - | SpecimenCode |
| SinkingTime | IfcPropertyListValue | IfcDuration | TIMEUNIT | SinkingTime |
| SuspensionTemperature | IfcPropertyListValue | IfcThermodynamicTemperatureMeasure | THERMODYNAMICTEMPERATUREUNIT | SuspensionTemperature |

| | | | | |
|---|---|---|---|---|
| FailingDistanceOfParticle | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | FailingDistanceOfParticle |
| MassPercentLessThanThisDia meter | IfcPropertyListValue | IfcRatioMeasure | - | MassPercentLessThanThisDi ameter |
| AccumulatedMassPercentLess Than ThisDiameter | IfcPropertyListValue | IfcRatioMeasure | - | AccumulatedMassPercentLes sThan ThisDiameter |
| ConstrainedGrainSize | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | ConstrainedGrainSize |
| AverageGrainSize | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | AverageGrainSize |
| EffectiveGrainSize | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | EffectiveGrainSize |
| CofficientOfNonuniformity | IfcPropertySingleValue | IfcReal | - | CofficientOfNonuniformity |
| CofficientOfGraduation | IfcPropertySingleValue | IfcReal | - | CofficientOfGraduation |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| Tester | IfcPropertyListValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertyListValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertyListValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceVal ue | | - | ReferencedSpecifications |

⑸Moisture content test

| | |
|---|---|
| **Property Set Name** | Pset_SoilSpecimenMoistureContentTestResult |
| **Applicable Entities** | **IfcSoilSpecimen** |

| **Applicable Type Value** | | | | |
|---|---|---|---|---|
| **Definition** | Result information of moisture content test by air dry method | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | - | ProcedureDescription |
| SpecimenCode | IfcPropertyListValue | IfcLabel | - | SpecimenCode |
| BoxCode | IfcPropertyListValue | IfcLabel | - | BoxCode |
| MassOfBox | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassOfBox |
| BoxMassWithWetSpecimen | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | BoxMassWithWetSpecimen |
| BoxMassWithDrySpecimen | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | BoxMassWithDrySpecimen |
| MassOfWater | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassOfWater |
| MassOfDrySpecimen | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassOfDrySpecimen |
| MoistureContent | IfcPropertyListValue | IfcReal | - | MoistureContent |
| AverageMoistureContent | IfcPropertySingleValue | IfcReal | - | AverageMoistureContent |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| Tester | IfcPropertyListValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertyListValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertyListValue | IfcLabel | - | Calculator |

| | | | | |
|---|---|---|---|---|
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

⑹Liquid and Plastic limit test property set

| **Property Set Name** | Pset_SoilSpecimenLiquidAndPlasticLimitTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcSoilSpecimen** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Result information of a set of liquid limit test sample | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | - | ProcedureDescription |
| SpecimenCode | IfcPropertyListValue | IfcLabel | - | SpecimenCode |
| BoxCode | IfcPropertyListValue | IfcLabel | - | BoxCode |
| MassOfBox | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassOfBox |
| BoxMassWithWetSpecimen | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | BoxMassWithWetSpecimen |
| BoxMassWithDrySpecimen | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | BoxMassWithDrySpecimen |
| MassOfWater | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassOfWater |
| MassOfDrySpecimen | IfcPropertyListValue | IfcMassMeasure | MASSUNIT | MassOfDrySpecimen |

| | | | | |
|---|---|---|---|---|
| MoistureContent | IfcPropertyListValue | IfcReal | - | MoistureContent |
| PlasticLimit | IfcPropertyListValue | IfcReal | - | PlasticLimit |
| LiquidLimit | IfcPropertyListValue | IfcReal | - | LiquidLimit |
| PlasticIndex | IfcPropertyListValue | IfcReal | - | PlasticIndex |
| LiquidIndex | IfcPropertyListValue | IfcReal | - | LiquidIndex |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| Tester | IfcPropertyListValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertyListValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertyListValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

(7)direct shear test

| **Property Set Name** | Pset_SoilSpecimenSheareBoxTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcSoilSpecimen** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Result information of a set of shear box test sample | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |

| | | | | |
|---|---|---|---|---|
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | - | ProcedureDescripti on |
| SpecimenName | IfcPropertyListValue | IfcLabel | - | SpecimenName |
| AuxometerCofficient | IfcPropertySingleValue | IfcReal | USERDEFINED | AuxometerCoffici ent |
| BoxCode | IfcPropertyListValue | IfcLabel | - | BoxCode |
| ShearType | IfcPropertyEnumeratedVal ue | IfcLabel | - | ShearType |
| AngleOfInternalFriction | IfcPropertySingleValue | IfcPlaneAngleMeasure | PLANEANGLEU NIT | AngleOfInternalFr iction |
| VerticalCompressiveStress | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | VerticalCompressi veStress |
| PeakShearStrength | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | PeakShearStrength |
| ConsolidationTime | IfcPropertyListValue | IfcDuration | TIMEUNIT | ConsolidationTime |
| ShearDuration | IfcPropertyListValue | IfcDuration | TIMEUNIT | ShearDuration |
| RotationRateOfHandwheel | IfcPropertyListValue | IfcAngularVelocityMeasu re | ANGULARVELO CITYUNIT | RotationRateOfHa ndwheel |
| CohesiveStrength | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | CohesiveStrength |
| MoistureContent | IfcPropertyListValue | IfcReal | - | MoistureContent |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| Tester | IfcPropertySingleValue | IfcLabel | - | Tester |

| | | | | |
|---|---|---|---|---|
| Proofreader | IfcPropertySingleValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertySingleValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

(8)Traxial compression test

| **Property Set Name** | Pset_SoilSpecimenTrialxiaConsolidationTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcSoilSpecimen** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Result information of a set traxial compression test sample | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | - | ProcedureDescription |
| TriaxialApparatusDetails | IfcPropertySingleValue | IfcLabel | - | TriaxialApparatusDetails |
| TestType | IfcPropertySingleValue | IfcLabel | - | TestType |
| SpecimenPreparationMethod | IfcPropertySingleValue | IfcLabel | - | SpecimenPreparationMethod |
| ConfiningPressure | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | ConfiningPressure |
| AxialFailureStrain | IfcPropertyListValue | IfcReal | - | AxialFailureStrain |

| | | | | |
|---|---|---|---|---|
| FailureMaxPrimaryStress | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | FailureMaxPrimaryStress |
| FailurePorewaterStress | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | FailurePorewaterStress |
| FailureEffectiveMaxPrimaryStress | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | FailureEffectiveMaxPrimaryStress |
| FailureEffectiveMinPrimaryStress | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | FailureEffectiveMinPrimaryStress |
| RatioOfEffectivePrimaryStress | IfcPropertyListValue | IfcReal | - | RatioOfEffectivePrimaryStress |
| FailureDescription | IfcPropertyListValue | IfcLabel | - | FailureDescription |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| Tester | IfcPropertyListValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertyListValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertyListValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

⑼Consolidation Test

| | |
|---|---|
| **Property Set Name** | Pset_SoilSpecimenConsolidationTestResult |
| **Applicable Entities** | **IfcSoilSpecimen** |
| **Applicable Type Value** | |
| **Definition** | Result information of a set consolidation test sample, applied to both standard consolidation and quick consolidation |

| Property Name | Property Type | Data Type | Unit | Definition |
|---|---|---|---|---|
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | - | ProcedureDescription |
| TestType | IfcPropertySingleValue | IfcLabel | - | TestType |
| ConsolidometerDetails | IfcPropertySingleValue | IfcLabel | - | ConsolidometerDetails |
| InitialVoidRatio | IfcPropertySingleValue | IfcReal | - | InitialVoidRatio |
| LoadStressList | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | LoadStressList |
| ConsolidatedVoidRatioForLoadRange | IfcPropertyListValue | IfcReal | - | ConsolidatedVoidRatioForLoadRange |
| CompressionFactorForLoadRange | IfcPropertyListValue | IfcReal | USERDEFINED | CompressionFactorForLoadRange |
| CompressionModulusForLoadRange | IfcPropertyListValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | CompressionModulusForLoadRange |
| VolumeCompressionModulusForLoadRange | IfcPropertyListValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | VolumeCompressionModulusForLoadRange |
| PreconsolidationPressure | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | PreconsolidationPressure |
| CompressionIndexForLoadRange | IfcPropertySingleValue | IfcReal | USERDEFINED | CompressionIndexForLoadRange |
| ResilientModulusForLoadRange | IfcPropertySingleValue | IfcModulusOfElasticityMea | MODULUSOFEL | ResilientModulusF |

| | | | | |
|---|---|---|---|---|
| | | sure | ASTICITYUNIT | orLoadRange |
| ConsolidationCofficient | IfcPropertySingleValue | IfcReal | USERDEFINED | ConsolidationCofficient |
| SolutionOfConsolidationCofficient | IfcPropertySingleValue | IfcLabel | - | SolutionOfConsolidationCofficient |
| PoissonRatio | IfcPropertySingleValue | IfcReal | - | PoissonRatio |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| Tester | IfcPropertySingleValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertySingleValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertySingleValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

⑽Static Lateral Pressure Cofficient Test

| **Property Set Name** | Pset_SoilSpecimenStaticLateralPressureCofficientTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcSoilSpecimen** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Result information of static lateral pressure coefficient test for a sample | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |

| | | | | |
|---|---|---|---|---|
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| SpecimenName | IfcPropertyListValue | IfcLabel | - | SpecimenName |
| TestDetails | IfcPropertyListValue | IfcLabel | - | TestDetails |
| EffectiveAxialCompressiveStress | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | EffectiveAxialCompressiveStress |
| EffectiveLateralCompressiveStress | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | EffectiveLateralCompressiveStress |
| StaticLateralPressureCofficient | IfcPropertySingleValue | IfcReal | - | StaticLateralPressureCofficient |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| Tester | IfcPropertyListValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertyListValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertyListValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

⑾Unconfined Compression Test

| | |
|---|---|
| **Property Set Name** | Pset_SoilSpecimenUnconfinedCompressionTestResult |
| **Applicable Entities** | **IfcSoilSpecimen** |
| **Applicable Type Value** | |
| **Definition** | Result information of uncondifined compression test for a set of sample |

| Property Name | Property Type | Data Type | Unit | Definition |
|---|---|---|---|---|
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| SpecimenName | IfcPropertyListValue | IfcLabel | - | SpecimenName |
| AxialStrainOfUndisturbedSoil | IfcPropertyListValue | IfcReal | - | AxialStrainOfUndisturbedSoil |
| AxialStressOfUndisturbedSoil | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | AxialStressOfUndisturbedSoil |
| FailureDetailOfUndisturbedSoil | IfcPropertyListValue | IfcLabel | - | FailureDetailOfUndisturbedSoil |
| AxialStrainOfRemoldedSoil | IfcPropertyListValue | IfcReal | - | AxialStrainOfRemoldedSoil |
| AxialStressOfRemoldedSoil | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | AxialStressOfRemoldedSoil |
| FailureDetailOfRemoldedSoil | IfcPropertyListValue | IfcLabel | - | FailureDetailOfRemoldedSoil |
| UnconfinedCompressiveStrengthOfUndisturbedSoil | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | UnconfinedCompressiveStrengthOfUndisturbedSoil |
| UnconfinedCompressiveStrengthOfRemoldedSoil | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | UnconfinedCompressiveStrengthOfRemoldedSoil |
| Sensitivity | IfcPropertySingleValue | IfcReal | - | Sensitivity |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |

| | | | | |
|---|---|---|---|---|
| Tester | IfcPropertyListValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertyListValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertyListValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

⑿Penetration test

| **Property Set Name** | Pset_SoilSpecimenPenetrationTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcSoilSpecimen** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Result information of penetration test for a set of sample | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| ProjectName | IfcPropertySingleValue | IfcLabel | - | ProjectName |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| SoilSampleName | IfcPropertySingleValue | IfcLabel | - | SoilSampleName |
| ProcedureDescription | IfcPropertySingleValue | IfcLabel | - | ProcedureDescription |
| SpecimenName | IfcPropertyListValue | IfcLabel | - | SpecimenName |
| TestType | IfcPropertySingleValue | IfcLabel | - | TestType |
| WaterTemperature | IfcPropertyListValue | IfcThermodynamicTemperatureMeasure | THERMODYNAMIC TEMPERATUREUNI | WaterTemperature |

| | | | | |
|---|---|---|---|---|
| | | | T | |
| PenetrationDirection | IfcPropertyListValue | IfcLabel | - | PenetrationDirection |
| CorrectedPenetrationCofficient | IfcPropertyListValue | IfcLinearVelocityMeasure | LINEARVELOCITYUNIT | CorrectedPenetrationCofficient |
| AveragePenetrationCofficient | IfcPropertySingleValue | IfcLinearVelocityMeasure | LINEARVELOCITYUNIT | AveragePenetrationCofficient |
| TestTime | IfcPropertyListValue | IfcDateTime | - | TestTime |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| Tester | IfcPropertyListValue | IfcLabel | - | Tester |
| Proofreader | IfcPropertyListValue | IfcLabel | - | Proofreader |
| Calculator | IfcPropertyListValue | IfcLabel | - | Calculator |
| TestUnit | IfcPropertyListValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

**In situ test information property set**

(1)StandardPenetrationTest Property Set

| **Property Set Name** | Pset_StandardPenetrationTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcBorehole** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Record of standard penetration test | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |

| | | | | |
|---|---|---|---|---|
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| TestTime | IfcPropertySingleValue | IfcDateTime | - | TestTime |
| TestEquipmentDetails | IfcPropertySingleValue | IfcText | - | TestEquipmentDetails |
| TestRange | IfcPropertySingleValue | IfcLabel | - | TestRange |
| TestElevation | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | TestElevation |
| StandardPenetrationBlowNumber | IfcPropertyListValue | IfcInteger | - | StandardPenetrationBlowNumber |
| AveragePenetrationBlowNumber | IfcPropertySingleValue | IfcInteger | - | AveragePenetrationBlowNumber |
| TestDetails | IfcPropertySingleValue | IfcLabel | - | TestDetails |
| TestRemark | IfcPropertySingleValue | IfcLabel | - | TestRemark |
| TestUnit | IfcPropertySingleValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

(2)Cone Dynamic Penetration Test Property Set

| **Property Set Name** | Pset_ConeDynamicPenetrationTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcBorehole** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Cone dynamic penetration test result information | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |

| | | | | |
|---|---|---|---|---|
| TestTime | IfcPropertySingleValue | IfcDateTime | - | TestTime |
| TestType | IfcPropertySingleValue | IfcLabel | - | TestType |
| TestElevation | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | TestElevation |
| BolowCountList | IfcPropertyListValue | IfcInteger | - | BolowCountList |
| AverageCount | IfcPropertySingleValue | IfcInteger | - | AverageCount |
| TestDetails | IfcPropertySingleValue | IfcText | - | TestDetails |
| TestRemark | IfcPropertySingleValue | IfcLabel | - | TestRemark |
| TestUnit | IfcPropertySingleValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

⑶Pressuremeter Test Property Set

| **Property Set Name** | Pset_PressuremeterTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcBorehole** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Pressuremeter test record | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| TestTime | IfcPropertySingleValue | IfcDateTime | - | TestTime |
| TestEquipmentDetails | IfcPropertySingleValue | IfcLabel | - | TestEquipmentDetails |
| TestElevation | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | TestElevation |

| | | | | |
|---|---|---|---|---|
| InitialPressure | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | InitialPressure |
| CriticalEdgePressure | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | CriticalEdgePressure |
| LimitPressure | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | LimitPressure |
| LimitBearingCapacilityOfCriticalEdgeMethod | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | LimitBearingCapacilityOfCriticalEdgeMethod |
| LimitBearingCapacilityOfLimitLoadMethod | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | LimitBearingCapacilityOfLimitLoadMethod |
| CriticalEdgeStrength | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | CriticalEdgeStrength |
| ShearModulusOfPressuremeter | IfcPropertySingleValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | ShearModulusOfPressuremeter |
| ModulusOfPressuremeter | IfcPropertySingleValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | ModulusOfPressuremeter |
| CompressionModulusByRatioMethod | IfcPropertySingleValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | CompressionModulusByRatioMethod |
| CompressionModulusByExperienceMethod | IfcPropertySingleValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | CompressionModulusByExperienceMethod |
| DeformationModulus | IfcPropertySingleValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | DeformationModulus |
| TestDetails | IfcPropertySingleValue | IfcText | - | TestDetails |
| TestRemark | IfcPropertySingleValue | IfcLabel | - | TestRemark |
| TestUnit | IfcPropertySingleValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

(4)Cone Penetration Test Property Set

| **Property Set Name** | Pset_ConePenetrationTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcBorehole,IfcStratum** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | A set of record for cone penetration test | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| LocationDetails | IfcPropertySingleValue | IfcLabel | - | LocationDetails |
| TestTime | IfcPropertySingleValue | IfcDateTime | - | TestTime |
| TestType | IfcPropertySingleValue | IfcLabel | - | TestType |
| ProbeType | IfcPropertySingleValue | IfcLabel | - | ProbeType |
| PenetrationDepth | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | PenetrationDepth |
| ConeResistance | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | ConeResistance |
| SpecificPenetrationResistance | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | SpecificPenetrationResistance |
| SideFricitionResistance | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | SideFricitionResistance |
| PoreWaterPressure | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | PoreWaterPressure |
| FricitionalRatio | IfcPropertyListValue | IfcReal | - | FricitionalRatio |
| JudgmentOfSoilType | IfcPropertyListValue | IfcReal | - | JudgmentOfSoilType |
| EstimatedHorizontalConsolidat | IfcPropertyListValue | IfcReal | USERDEFINED | EstimatedHorizontalCo |

| | | | | |
|---|---|---|---|---|
| inoCofficient | | | | nsolidatinoCofficient |
| EstimatedUndrainedShearStrength | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | EstimatedUndrainedShearStrength |
| EstimatedInternalFricitionAngleOfSand | IfcPropertyListValue | IfcPlaneAngleMeasure | PLANEANGLEUNIT | EstimatedInternalFricitionAngleOfSand |
| EstimatedCompressionModulusOfSand | IfcPropertyListValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | EstimatedCompressionModulusOfSand |
| EstimatedCompressionModulusOfClay | IfcPropertyListValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | EstimatedCompressionModulusOfClay |
| EstimatedDeformationModulusOfClay | IfcPropertyListValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | EstimatedDeformationModulusOfClay |
| TestDetails | IfcPropertySingleValue | IfcText | - | TestDetails |
| TestRemark | IfcPropertySingleValue | IfcLabel | - | TestRemark |
| TestUnit | IfcPropertySingleValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

⑸Loading Test Property Set

| | |
|---|---|
| **Property Set Name** | Pset_LoadingTestResult |
| **Applicable Entities** | **IfcBorehole,IfcStratum** |
| **Applicable Type Value** | |
| **Definition** | A set of record for Loading test |

| Property Name | Property Type | Data Type | Unit | Definition |
|---|---|---|---|---|
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| LocationDetails | IfcPropertySingleValue | IfcLabel | - | LocationDetails |
| TestTime | IfcPropertySingleValue | IfcDateTime | - | TestTime |
| TestType | IfcPropertySingleValue | IfcLabel | - | TestType |
| ShapeOfBearingPlate | IfcPropertySingleValue | IfcLabel | - | ShapeOfBearingPlate |
| DiameterOfBearingPlate | IfcPropertySingleValue | IfcLengthMeasure | LENGTHUNIT | DiameterOfBearingPlate |
| LoadMethod | IfcPropertySingleValue | IfcLabel | - | LoadMethod |
| LoadList | IfcPropertyListValue | IfcForceMeasure | FORCEUNIT | LoadList |
| SettlementList | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | SettlementList |
| SettlementDurationList | IfcPropertyListValue | IfcDuration | TIMEUNIT | SettlementDurationList |
| FoundationBearingCapacityValue | IfcPropertySingleValue | IfcPressureMeasure | PRESSUREUNIT | FoundationBearingCapacityValue |
| DeformationModulus | IfcPropertySingleValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | DeformationModulus |
| SubgradeReactionCoefficient | IfcPropertySingleValue | IfcReal | USERDEFINED | SubgradeReactionCoefficient |
| CorrectedSubgradeReactionCofficient | IfcPropertySingleValue | IfcReal | USERDEFINED | CorrectedSubgradeReactionCofficient |
| HorizontalConsolidationCofficient | IfcPropertySingleValue | IfcReal | USERDEFINED | HorizontalConsolidationCofficient |
| TestDetails | IfcPropertySingleValue | IfcText | - | TestDetails |

| | | | | |
|---|---|---|---|---|
| TestRemark | IfcPropertySingleValue | IfcLabel | - | TestRemark |
| TestUnit | IfcPropertySingleValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

⑹DilatometerTest Property Set

| **Property Set Name** | Pset_DilatometerTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcBorehole,IfcStratum** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | A set of record for dilatometer test | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| LocatioDetails | IfcPropertySingleValue | IfcLabel | - | LocatioDetails |
| TestTime | IfcPropertySingleValue | IfcDateTime | - | TestTime |
| TestElevation | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | TestElevation |
| HorizontalStressIndex | IfcPropertyListValue | IfcReal | - | HorizontalStressIndex |
| SoilIndex | IfcPropertyListValue | IfcReal | - | SoilIndex |
| SideSwellingModuls | IfcPropertyListValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | SideSwellingModuls |
| StaticLateralStressCofficient | IfcPropertyListValue | IfcReal | - | StaticLateralStressCofficient |

| | | | | |
|---|---|---|---|---|
| UndrainedShearStrength | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | UndrainedShearStrength |
| CofficientOfLateralSubgradeReaction | IfcPropertyListValue | IfcReal | USERDEFINED | CofficientOfLateralSubgradeReaction |
| HorizontalConsolidationCoffici ent | IfcPropertyListValue | IfcReal | USERDEFINED | HorizontalConsolidation Cofficient |
| CompressionModuls | IfcPropertyListValue | IfcModulusOfElasticityMeasure | MODULUSOFELASTICITYUNIT | CompressionModuls |
| TestDetails | IfcPropertySingleValue | IfcText | - | TestDetails |
| TestRemark | IfcPropertySingleValue | IfcLabel | - | TestRemark |
| TestUnit | IfcPropertySingleValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

(7)Vane Shear Test Property Set

| **Property Set Name** | Pset_VaneShearTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcBorehole,IfcStratum** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | A set of record for Vane Shear Test | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| LocationDetails | IfcPropertySingleValue | IfcLabel | - | LocationDetails |
| TestTime | IfcPropertySingleValue | IfcDateTime | - | TestTime |

| | | | | |
|---|---|---|---|---|
| TestType | IfcPropertySingleValue | IfcTabel | - | TestType |
| TestElevation | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | TestElevation |
| ShearStrengthOfUndisturbedSoil | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | ShearStrengthOfUndisturbedSoil |
| CorrectedShearStrengthOfUndisturbedSoil | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | CorrectedShearStrengthOfUndisturbedSoil |
| ShearStrengthOfRemoldedSoil | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | ShearStrengthOfRemoldedSoil |
| CorrectedShearStrengthOfRemoldedSoil | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | CorrectedShearStrengthOfRemoldedSoil |
| Sensitivity | IfcPropertyListValue | IfcReal | - | Sensitivity |
| TestDetails | IfcPropertySingleValue | IfcText | - | TestDetails |
| TestRemark | IfcPropertySingleValue | IfcLabel | - | TestRemark |
| TestUnit | IfcPropertySingleValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

(8)Field Direct Shear Test Property Set

| **Property Set Name** | Pset_FieldDirectShearTestResult | | | |
|---|---|---|---|---|
| **Applicable Entities** | **IfcBorehole,IfcStratum** | | | |
| **Applicable Type Value** | | | | |
| **Definition** | Field direct shear test record | | | |
| **Property Name** | **Property Type** | **Data Type** | **Unit** | **Definition** |
| StratumCode | IfcPropertySingleValue | IfcLabel | - | StratumCode |

| | | | | |
|---|---|---|---|---|
| BoreholeName | IfcPropertySingleValue | IfcLabel | - | BoreholeName |
| LocationDetails | IfcPropertySingleValue | IfcLabel | - | LocationDetails |
| TestTime | IfcPropertySingleValue | IfcDateTime | - | TestTime |
| TestType | IfcPropertySingleValue | IfcTabel | - | TestType |
| TestElevation | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | TestElevation |
| ShearPlaneDescription | IfcPropertyListValue | IfcText | - | ShearPlaneDescription |
| NormalLoad | IfcPropertyListValue | IfcForceMeasure | FORCEUNIT | NormalLoad |
| NormalStress | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | NormalStress |
| ShearStress | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | ShearStress |
| ShearDisplacement | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | ShearDisplacement |
| PeakShearStrength | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | PeakShearStrength |
| ResidualShearStrength | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | ResidualShearStrength |
| VerticalDispalcement | IfcPropertyListValue | IfcLengthMeasure | LENGTHUNIT | VerticalDispalcement |
| DilatancyStrength | IfcPropertyListValue | IfcPressureMeasure | PRESSUREUNIT | DilatancyStrength |
| FailureDescriptionOfShearPlane | IfcPropertyListValue | IfcText | - | FailureDescriptionOfShearPlane |
| TestDetails | IfcPropertySingleValue | IfcText | - | TestDetails |
| TestRemark | IfcPropertySingleValue | IfcLabel | - | TestRemark |

| | | | | |
|---|---|---|---|---|
| TestUnit | IfcPropertySingleValue | IfcLabel | - | TestUnit |
| ReferencedSpecifications | IfcComplexProperty /IfcPropertyReferenceValue | | - | ReferencedSpecifications |

## Appendix C RDF example of Eric Miller

For example, here is a Person identified by http://www.w3.org/People/EM/contact#me, whose name is Eric Miller, whose email address is e.miller123(at)example (changed for security purposes), and whose title is Dr. The resource "http://www.w3.org/People/EM/contact#me" is the subject. The objects are: Eric Miller" (with a predicate "whose name is"),
mailto:e.miller123(at)example (with a predicate "whose email address is"), and
"Dr." (with a predicate "whose title is").
The subject is a URI.
The predicates also have URIs. For example, the URI for each predicate:
"whose name is" is http://www.w3.org/2000/10/swap/pim/contact#fullName,
"whose email address is" is http://www.w3.org/2000/10/swap/pim/contact#mailbox,
"whose title is" is http://www.w3.org/2000/10/swap/pim/contact#personalTitle.
In addition, the subject has a type (with URI http://www.w3.org/1999/02/22-rdf-syntax-ns#type), which is person (with URI http://www.w3.org/2000/10/swap/pim/contact#Person).
Therefore, the following "subject, predicate, object" RDF triples can be expressed:

http://www.w3.org/People/EM/contact#me, http://www.w3.org/2000/10/swap/pim/contact#fullName, "Eric Miller"

http://www.w3.org/People/EM/contact#me, http://www.w3.org/2000/10/swap/pim/contact#mailbox, mailto:e.miller123(at)example

http://www.w3.org/People/EM/contact#me, http://www.w3.org/2000/10/swap/pim/contact#personalTitle, "Dr."

http://www.w3.org/People/EM/contact#me, http://www.w3.org/1999/02/22-rdf-syntax-ns#type, http://www.w3.org/2000/10/swap/pim/contact#Person

In standard N-Triples format, this RDF can be written as:

<http://www.w3.org/People/EM/contact#me> <http://www.w3.org/2000/10/swap/pim/contact#fullName> "Eric Miller" .

<http://www.w3.org/People/EM/contact#me> <http://www.w3.org/2000/10/swap/pim/contact#mailbox> <mailto:e.miller123(at)example> .

<http://www.w3.org/People/EM/contact#me> <http://www.w3.org/2000/10/swap/pim/contact#personalTitle> "Dr." .

<http://www.w3.org/People/EM/contact#me> <http://www.w3.org/1999/02/22-rdf-syntax-ns#type> <http://www.w3.org/2000/10/swap/pim/contact#Person> .

Equivalently, it can be written in standard Turtle (syntax) format as:

```
@prefix eric:    <http://www.w3.org/People/EM/contact#> .

@prefix contact: <http://www.w3.org/2000/10/swap/pim/contact#> .

@prefix rdf:     <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .

eric:me contact:fullName "Eric Miller" .

eric:me contact:mailbox <mailto:e.miller123(at)example> .

eric:me contact:personalTitle "Dr." .

eric:me rdf:type contact:Person .
```

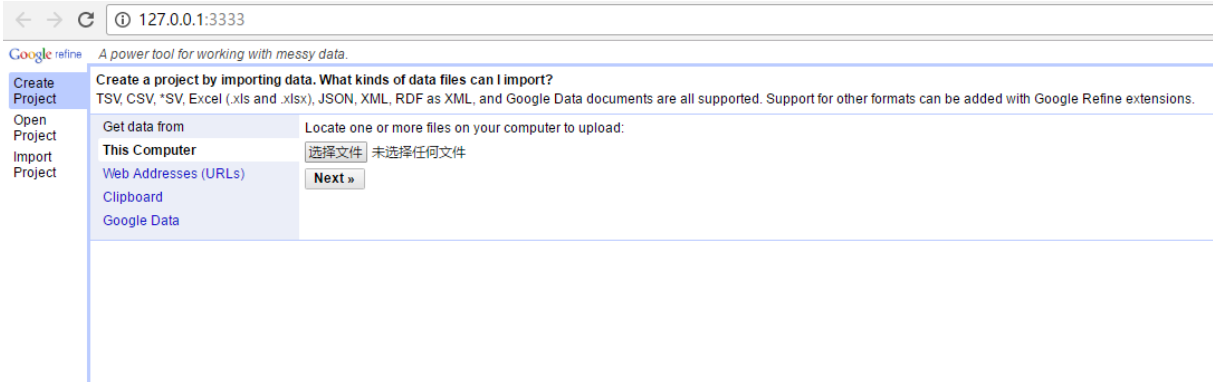
Or, it can be written in RDF/XML format as:

```
<?xml version="1.0" encoding="utf-8"?>

<rdf:RDF xmlns:contact="http://www.w3.org/2000/10/swap/pim/contact#"
xmlns:eric="http://www.w3.org/People/EM/contact#" xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#">

  <rdf:Description rdf:about="http://www.w3.org/People/EM/contact#me">

    <contact:fullName>Eric Miller</contact:fullName>

  </rdf:Description>

  <rdf:Description rdf:about="http://www.w3.org/People/EM/contact#me">
```

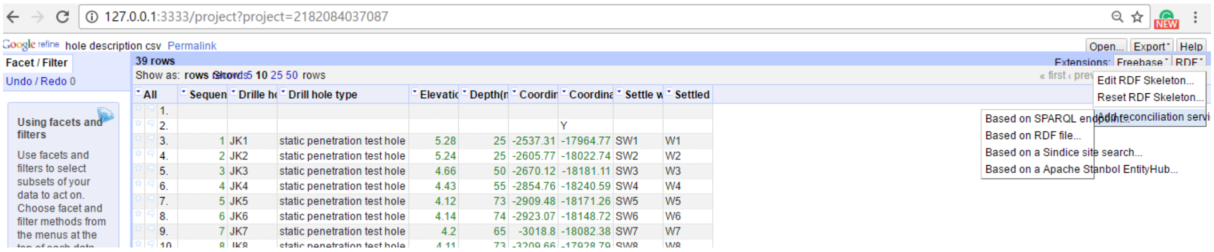
```
    <contact:mailbox rdf:resource="mailto:e.miller123(at)example"/>

  </rdf:Description>

  <rdf:Description rdf:about="http://www.w3.org/People/EM/contact#me">

    <contact:personalTitle>Dr.</contact:personalTitle>

  </rdf:Description>

  <rdf:Description rdf:about="http://www.w3.org/People/EM/contact#me">

    <rdf:type rdf:resource="http://www.w3.org/2000/10/swap/pim/contact#Person"/>

  </rdf:Description>

</rdf:RDF>
```

## Appendix D csv file converting to ttl file process

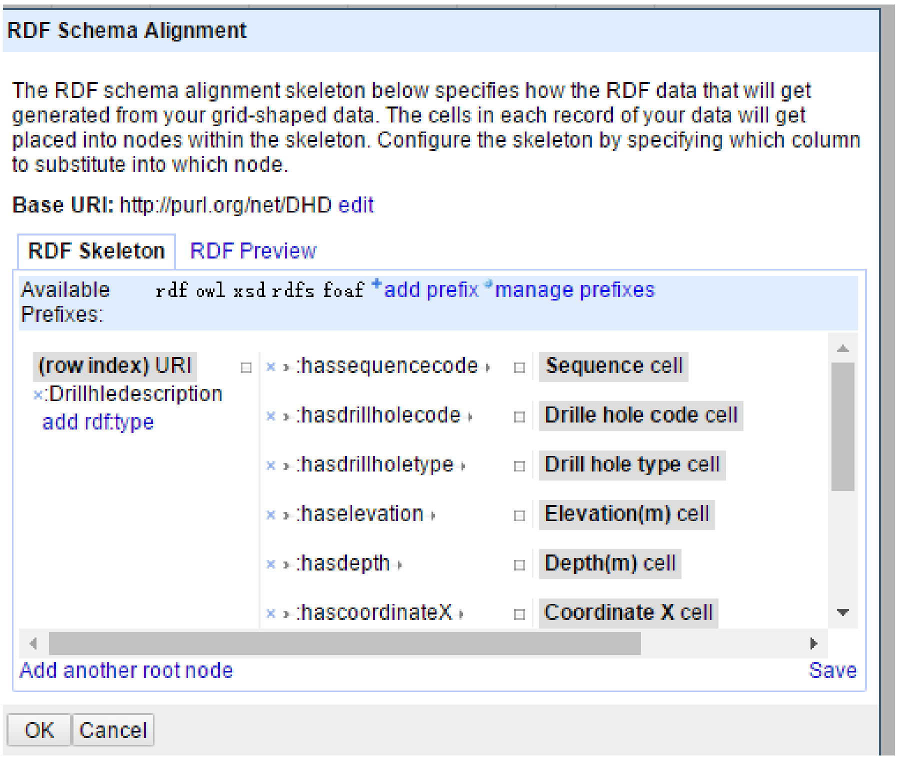
Step 1 create a project and then upload the file



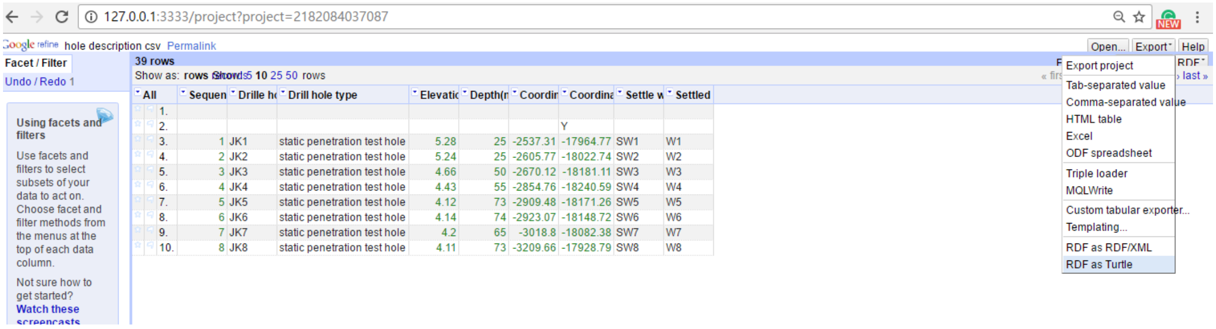

Step 2 with the RDF extension, open refine is able to edit RDF files, click the “Eidt RDF Skeleton”




Step 3 construct RDF skeleton with the structure of self-design ontology



Step 4 Export RDF as Turtle



## Appendix E self-defined RDF ontology (before data linking process)

### a. Drill hole Description ontology

```
@prefix DHD: <http://purl.org/net/DHD#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .


<http://purl.org/net/DHD#> rdf:type owl:Ontology .

#################################################################
#    Data properties
#################################################################

###  http://purl.org/net/DHD#hascoordinateX
DHD:hascoordinateX rdf:type owl:DatatypeProperty ;
                                  rdfs:domain DHD:Drillhole ;
                                  rdfs:range xsd:double ;
                                  rdfs:comment "a relation identify the
location of the drill hole with coordinate X in the relative local reference
system"^^xsd:string ;
                                  rdfs:label "hascoordinateX"^^xsd:string .


###  http://purl.org/net/DHD#hascoordinateY
DHD:hascoordinateY rdf:type owl:DatatypeProperty ;
                                  rdfs:domain DHD:Drillhole  ;
                                  rdfs:range xsd:double ;
                                  rdfs:comment "a relation identify the
location of the drill hole with coordinate Y in the relative local reference
system"^^xsd:string ;
                                  rdfs:label "hascoordinateY"^^xsd:string .


###  http://purl.org/net/DHD#hasdepth
DHD:hasdepth rdf:type owl:DatatypeProperty ;
```

```
                              rdfs:domain DHD:Drillhole  ;
                              rdfs:range xsd:float ;
                              rdfs:comment "a relation identify the depth of
drill hole"^^xsd:string ;
                              rdfs:label "hasdepth"^^xsd:string .


###  http://purl.org/net/DHD#hasdrillholecode
DHD:hasdrillholecode rdf:type owl:DatatypeProperty ;
                                     rdfs:domain
<http://purl.org/net/DHD#Drillhole> ;
                                     rdfs:range xsd:string ;
                                     rdfs:comment "a relation to identify the
ID of drill hole"^^xsd:string ;
                                     rdfs:label
"hasdrillholecode"^^xsd:string .


###  http://purl.org/net/DHD#hasdrillholetype
DHD:hasdrillholetype rdf:type owl:DatatypeProperty ;
                                     rdfs:domain DHD:Drillhole  ;
                                     rdfs:range xsd:string ;
                                     rdfs:comment "a relation to identify the
purpose and contsruction of drill hole"^^xsd:string ;
                                     rdfs:label
"hasdrillholetype"^^xsd:string .


###  http://purl.org/net/DHD#haselevation
DHD:haselevation rdf:type owl:DatatypeProperty ;
                                 rdfs:domain DHD:Drillhole  ;
                                 rdfs:range xsd:float ;
                                 rdfs:comment "a relation to identify the
elevation of drill hole"^^xsd:string ;
                                 rdfs:label "haselevation"^^xsd:string .


###  http://purl.org/net/DHD#hostgroundsettlementsensor
DHD:hostgroundsettlementsensor rdf:type owl:DatatypeProperty ;
                                          rdfs:domain DHD:Drillhole  ;
                                          rdfs:range xsd:string ;
                                          rdfs:comment "a relation to
identify the ground settlement sensor in the hole"^^xsd:string ;
```

```
                                                rdfs:label
"hostgroundsettlementsensor"^^xsd:string .


###  http://purl.org/net/DHD#hostwaterlevelsensor
DHD:hostwaterlevelsensor rdf:type owl:DatatypeProperty ;
                                       rdfs:domain DHD:Drillhole  ;
                                       rdfs:range xsd:string ;
                                       rdfs:comment "a relation to identify
the water level snesor in the hole"^^xsd:string ;
                                       rdfs:label
"hostwaterlevelsensor"^^xsd:string .


#################################################################
#    Classes
#################################################################

###  http://purl.org/net/DHD#Drillhole
DHD:Drillhole rdf:type owl:Class ;
                              rdfs:comment "an object to identify the sampling
site and geosensor container"^^xsd:string ;
                              rdfs:label "DrillHole"^^xsd:string .
```

## b. Geo sensor ontology

```
@prefix : <http://purl.org/net/Geosensor##> .
@prefix GS: <http://purl.org/net/Geosensor#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@base <http://purl.org/net/Geosensor#> .

<http://purl.org/net/Geosensor#> rdf:type owl:Ontology ;
                              rdfs:comment "The ontology describes geosensor's
relationship" .

#################################################################
#    Data properties
#################################################################
```

```
###  http://purl.org/net/Geosensor#hasmeasruingdate
GS:hasmeasruingdate rdf:type owl:DatatypeProperty ;
                 rdfs:domain GS:Geosensor ;
                 rdfs:range xsd:dateTime ;
                 rdfs:comment "a relation identify the date of conducting
measuring"^^xsd:string ;
                 rdfs:label "hasmeasuringdate"^^xsd:string .


###  http://purl.org/net/Geosensor#hasmeasuringvalue
GS:hasmeasuringvalue rdf:type owl:DatatypeProperty ;
                  rdfs:domain GS:Geosensor ;
                  rdfs:range xsd:double ;
                  rdfs:comment "a relation to indicate the sensor's sensing
value"^^xsd:string ;
                  rdfs:label "hasmeasuringvalue"^^xsd:string .


#################################################################
#    Classes
#################################################################

###  http://purl.org/net/Geosensor#Geosensor
GS:Geosensor rdf:type owl:Class ;
           rdfs:comment "An object to monitoring geological related
data"^^xsd:string .


###  http://purl.org/net/Geosensor#Groundsettlementsensor
GS:Groundsettlementsensor rdf:type owl:Class ;
                       rdfs:subClassOf GS:Geosensor ;
                       owl:disjointWith GS:Waterlevelsensor ;
                       rdfs:comment "An object to detect ground
settlement"^^xsd:string .


###  http://purl.org/net/Geosensor#SW1
GS:SW1 rdf:type owl:Class ;
      rdfs:subClassOf GS:Waterlevelsensor ;
      rdfs:label "SW1"^^xsd:string .


###  http://purl.org/net/Geosensor#SW10
```

```
GS:SW10 rdf:type owl:Class ;
       rdfs:subClassOf GS:Waterlevelsensor ;
       rdfs:label "SW10"^^xsd:string .


###  http://purl.org/net/Geosensor#SW11
GS:SW11 rdf:type owl:Class ;
       rdfs:subClassOf GS:Waterlevelsensor ;
       rdfs:label "SW11"^^xsd:string .


###  http://purl.org/net/Geosensor#SW12
GS:SW12 rdf:type owl:Class ;
       rdfs:subClassOf GS:Waterlevelsensor ;
       rdfs:label "SW12"^^xsd:string .


###  http://purl.org/net/Geosensor#SW13
GS:SW13 rdf:type owl:Class ;
       rdfs:subClassOf GS:Waterlevelsensor ;
       rdfs:label "SW13"^^xsd:string .


###  http://purl.org/net/Geosensor#SW14
GS:SW14 rdf:type owl:Class ;
       rdfs:subClassOf GS:Waterlevelsensor ;
       rdfs:label "SW14"^^xsd:string .


###  http://purl.org/net/Geosensor#SW15
GS:SW15 rdf:type owl:Class ;
       rdfs:subClassOf GS:Waterlevelsensor ;
       rdfs:label "SW15"^^xsd:string .


###  http://purl.org/net/Geosensor#SW16
GS:SW16 rdf:type owl:Class ;
       rdfs:subClassOf GS:Waterlevelsensor ;
       rdfs:label "SW16"^^xsd:string .


###  http://purl.org/net/Geosensor#SW17
GS:SW17 rdf:type owl:Class ;
       rdfs:subClassOf GS:Waterlevelsensor ;
```

```
       rdfs:label "SW17"^^xsd:string .


### http://purl.org/net/Geosensor#SW18
GS:SW18 rdf:type owl:Class ;
       rdfs:subClassOf GS:Waterlevelsensor ;
       rdfs:label "SW18"^^xsd:string .


### http://purl.org/net/Geosensor#SW2
GS:SW2 rdf:type owl:Class ;
      rdfs:subClassOf GS:Waterlevelsensor ;
      rdfs:label "SW2"^^xsd:string .


### http://purl.org/net/Geosensor#SW3
GS:SW3 rdf:type owl:Class ;
      rdfs:subClassOf GS:Waterlevelsensor ;
      rdfs:label "SW3"^^xsd:string .


### http://purl.org/net/Geosensor#SW4
GS:SW4 rdf:type owl:Class ;
      rdfs:subClassOf GS:Waterlevelsensor ;
      rdfs:label "SW4"^^xsd:string .


### http://purl.org/net/Geosensor#SW5
GS:SW5 rdf:type owl:Class ;
      rdfs:subClassOf GS:Waterlevelsensor ;
      rdfs:label "SW5"^^xsd:string .


### http://purl.org/net/Geosensor#SW6
GS:SW6 rdf:type owl:Class ;
      rdfs:subClassOf GS:Waterlevelsensor ;
      rdfs:label "SW6"^^xsd:string .


### http://purl.org/net/Geosensor#SW7
GS:SW7 rdf:type owl:Class ;
      rdfs:subClassOf GS:Waterlevelsensor ;
      rdfs:label "SW7"^^xsd:string .
```

```
###  http://purl.org/net/Geosensor#SW8
GS:SW8 rdf:type owl:Class ;
      rdfs:subClassOf GS:Waterlevelsensor ;
      rdfs:label "SW8"^^xsd:string .


###  http://purl.org/net/Geosensor#SW9
GS:SW9 rdf:type owl:Class ;
      rdfs:subClassOf GS:Waterlevelsensor ;
      rdfs:label "SW9"^^xsd:string .


###  http://purl.org/net/Geosensor#W1
GS:W1 rdf:type owl:Class ;
     rdfs:subClassOf GS:Groundsettlementsensor ;
     rdfs:label "W1"^^xsd:string .


###  http://purl.org/net/Geosensor#W10
GS:W10 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W10"^^xsd:string .


###  http://purl.org/net/Geosensor#W11
GS:W11 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W11"^^xsd:string .


###  http://purl.org/net/Geosensor#W12
GS:W12 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W12"^^xsd:string .


###  http://purl.org/net/Geosensor#W13
GS:W13 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W13"^^xsd:string .


###  http://purl.org/net/Geosensor#W14
```

```
GS:W14 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W14"^^xsd:string .


###  http://purl.org/net/Geosensor#W15
GS:W15 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W15"^^xsd:string .


###  http://purl.org/net/Geosensor#W16
GS:W16 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W16"^^xsd:string .


###  http://purl.org/net/Geosensor#W17
GS:W17 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W17"^^xsd:string .


###  http://purl.org/net/Geosensor#W18
GS:W18 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W18"^^xsd:string .


###  http://purl.org/net/Geosensor#W19
GS:W19 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W19"^^xsd:string .


###  http://purl.org/net/Geosensor#W2
GS:W2 rdf:type owl:Class ;
     rdfs:subClassOf GS:Groundsettlementsensor ;
     rdfs:label "W2"^^xsd:string .


###  http://purl.org/net/Geosensor#W20
GS:W20 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
```

```
      rdfs:label "W20"^^xsd:string .


###  http://purl.org/net/Geosensor#W21
GS:W21 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W21"^^xsd:string .


###  http://purl.org/net/Geosensor#W22
GS:W22 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W22"^^xsd:string .


###  http://purl.org/net/Geosensor#W23
GS:W23 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W23"^^xsd:string .


###  http://purl.org/net/Geosensor#W24
GS:W24 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W24"^^xsd:string .


###  http://purl.org/net/Geosensor#W25
GS:W25 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W25"^^xsd:string .


###  http://purl.org/net/Geosensor#W26
GS:W26 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W26"^^xsd:string .


###  http://purl.org/net/Geosensor#W27
GS:W27 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W27"^^xsd:string .
```

```
###  http://purl.org/net/Geosensor#W28
GS:W28 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W28"^^xsd:string .


###  http://purl.org/net/Geosensor#W29
GS:W29 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W29"^^xsd:string .


###  http://purl.org/net/Geosensor#W3
GS:W3 rdf:type owl:Class ;
     rdfs:subClassOf GS:Groundsettlementsensor ;
     rdfs:label "W3"^^xsd:string .


###  http://purl.org/net/Geosensor#W30
GS:W30 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W30"^^xsd:string .


###  http://purl.org/net/Geosensor#W31
GS:W31 rdf:type owl:Class ;
      rdfs:subClassOf GS:Groundsettlementsensor ;
      rdfs:label "W31"^^xsd:string .


###  http://purl.org/net/Geosensor#W4
GS:W4 rdf:type owl:Class ;
     rdfs:subClassOf GS:Groundsettlementsensor ;
     rdfs:label "W4"^^xsd:string .


###  http://purl.org/net/Geosensor#W5
GS:W5 rdf:type owl:Class ;
     rdfs:subClassOf GS:Groundsettlementsensor ;
     rdfs:label "W5"^^xsd:string .


###  http://purl.org/net/Geosensor#W6
```

```
GS:W6 rdf:type owl:Class ;
     rdfs:subClassOf GS:Groundsettlementsensor ;
     rdfs:label "W6"^^xsd:string .


###  http://purl.org/net/Geosensor#W7
GS:W7 rdf:type owl:Class ;
     rdfs:subClassOf GS:Groundsettlementsensor ;
     rdfs:label "W7"^^xsd:string .


###  http://purl.org/net/Geosensor#W8
GS:W8 rdf:type owl:Class ;
     rdfs:subClassOf GS:Groundsettlementsensor ;
     rdfs:label "W8"^^xsd:string .


###  http://purl.org/net/Geosensor#W9
GS:W9 rdf:type owl:Class ;
     rdfs:subClassOf GS:Groundsettlementsensor ;
     rdfs:label "W9"^^xsd:string .


###  http://purl.org/net/Geosensor#Waterlevelsensor
GS:Waterlevelsensor rdf:type owl:Class ;
                 rdfs:subClassOf GS:Geosensor ;
                 rdfs:comment "an object to detect water level"^^xsd:string .
```

## c. Sensor description ontology

```
@prefix SD: <http://purl.org/net/SD#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .


<http://purl.org/net/SD> rdf:type owl:Ontology ;
                      rdfs:comment "An ontology to describe the sensor
descriptive data"^^xsd:string .
```

```
#################################################################
#    Data properties
#################################################################

###  http://purl.org/net/SD#hassensorcode
SD:hassensorcode rdf:type owl:DatatypeProperty ;
             rdfs:domain SD:SensorDescription ;
             rdfs:range xsd:string ;
             rdfs:comment "a relation to identify the sensor ID"^^xsd:string ;
             rdfs:label "hasensorcode"^^xsd:string .


###  http://purl.org/net/SD#servedpurpose
SD:servedpurpose rdf:type owl:DatatypeProperty ;
             rdfs:domain SD:SensorDescription ;
             rdfs:range xsd:string ;
             rdfs:comment "a relation to identify the sensening data's
usage"^^xsd:string ;
             rdfs:label "servedpurpose"^^xsd:string .


#################################################################
#    Classes
#################################################################

###  http://purl.org/net/SD#SensorDescription
SD:SensorDescription rdf:type owl:Class ;
                rdfs:comment "an object to identify the sensor descriptive data
file"^^xsd:string ;
                rdfs:label "sensordescription"^^xsd:string .
```

# Appendix F example data sets

Example data set for water level monitoring data SW1

| Checking date | value |
|---|---|
| 2016/1/7 | -3.46 |
| 2016/1/14 | -3.8 |
| 2016/1/21 | -4.1 |
| 2016/1/28 | -3.81 |
| 2016/2/4 | -2.983 |
| 2016/2/11 | -2.932 |
| 2016/2/23 | -2.942 |
| 2016/3/2 | -3.004 |
| 2016/3/9 | -3.056 |
| 2016/3/16 | -3 |
| 2016/3/23 | -3.11 |
| 2016/3/30 | -3.16 |
| 2016/4/6 | -3.185 |
| 2016/4/13 | -3.196 |
| 2016/4/20 | -3.232 |
| 2016/4/27 | -3.231 |
| 2016/5/3 | -3.268 |
| 2016/5/10 | -3.221 |
| 2016/5/17 | -3.195 |
| 2016/5/23 | -3.235 |
| 2016/5/30 | -3.28 |
| 2016/6/6 | -2.179 |
| 2016/6/13 | -2.283 |
| 2016/6/20 | -2.321 |
| 2016/6/27 | -2.15 |
| 2016/7/3 | -2.137 |
| 2016/7/10 | -2.183 |
| 2016/7/17 | -2.21 |
| 2016/7/23 | -2.223 |
| 2016/7/30 | -2.286 |
| 2016/8/7 | -2.248 |
| 2016/8/14 | -2.227 |
| 2016/8/21 | -2.245 |
| 2016/8/28 | -1.778 |
| 2016/9/4 | -1.555 |
| 2016/9/11 | -1.615 |
| 2016/9/18 | -1.64 |
| 2016/9/25 | -1.728 |
| 2016/10/2 | -1.782 |
| 2016/10/9 | -1.78 |
| 2016/10/16 | -2.15 |
| 2016/10/23 | -2.574 |
| 2016/10/30 | -2.351 |
| 2016/11/7 | -4.12 |
| 2016/11/13 | -4.137 |
| 2016/11/20 | -4.157 |
| 2016/11/27 | -4.157 |
| 2016/12/3 | refill |

Example data set of Drill Hole Description

| Drill hole type | Elevation | Depth(m) | Coordinate X | Coordinate Y | Settle water level monitoring sensor | Settled ground settlement monitoring sensor |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | Y | | |
| static penetration test hole | 5.28 | 25 | -2537.31 | -17964.77 | SW1 | W1 |
| static penetration test hole | 5.24 | 25 | -2605.77 | -18022.74 | SW2 | W2 |
| static penetration test hole | 4.66 | 50 | -2670.12 | -18181.11 | SW3 | W3 |
| static penetration test hole | 4.43 | 55 | -2854.76 | -18240.59 | SW4 | W4 |
| static penetration test hole | 4.12 | 73 | -2909.48 | -18171.26 | SW5 | W5 |
| static penetration test hole | 4.14 | 74 | -2923.07 | -18148.72 | SW6 | W6 |
| static penetration test hole | 4.2 | 65 | -3018.8 | -18082.38 | SW7 | W7 |
| static penetration test hole | 4.11 | 73 | -3209.66 | -17928.79 | SW8 | W8 |
| static penetration test hole | 4.6 | 83 | -3423.49 | -17757.52 | SW9 | W9 |
| static penetration test hole | 4.41 | 70 | -3731.89 | -17544.18 | SW10 | W10 |
| static penetration test hole | 3.87 | 65 | -3922.46 | -17393.7 | SW11 | W11 |
| static penetration test hole | 5.35 | 72 | -4019.27 | -17267.27 | SW12 | W12 |
| static penetration test hole | 4.43 | 55 | -4073.81 | -17202.59 | SW13 | W13 |
| static penetration test hole | 4.36 | 50 | -4215.9 | -17048.6 | SW14 | W14 |
| static penetration test hole | 3.88 | 50 | -4360.92 | -16950.17 | SW15 | W15 |
| static penetration test hole | 5.04 | 50 | -4443.99 | -16924.7 | SW16 | W16 |
| static penetration test hole | 4.52 | 31 | -4610.21 | -16826.54 | SW17 | W17 |
| static penetration test hole | 3.96 | 50 | -3875.7 | -17279.33 | SW18 | W18 |
| boring hole | 4.18 | 50 | -2594.04 | -18125.73 | | W19 |
| boring hole | 4.35 | 50.5 | -2652.8 | -18283 | | W20 |
| boring hole | 3.98 | 55 | -2758.11 | -18285.66 | | W21 |
| boring hole | 4.16 | 75 | -2942.59 | -18186.07 | | W22 |
| boring hole | 4.24 | 75 | -3137.5 | -18015.98 | | W23 |
| boring hole | 4.79 | 85 | -3331.87 | -17863.45 | | W24 |
| boring hole | 4.52 | 80.3 | -3533.68 | -17708.04 | | W25 |
| boring hole | 3.99 | 75 | -3633.43 | -17589.34 | | W26 |
| boring hole | 4.01 | 65.5 | -3812.05 | -17445.37 | | W27 |
| boring hole | 6 | 75 | -3996.25 | -17292.37 | | W28 |
| boring hole | 4.87 | 75 | -4040.96 | -17293.49 | | W29 |
| boring hole | 4.14 | 50 | -4172.51 | -17159.85 | | W30 |
| boring hole | 5.21 | 50 | -4302.4 | -17029.33 | | W31 |
| boring hole | 4.32 | 50 | -4526.08 | -16827.28 | | W32 |
| boring hole | 4.33 | 25 | -4647.25 | -16763.69 | | W33 |
| flat dilatometer hole | 4.18 | 35 | -4173.51 | -17157.85 | | |

## Appendix G Java code

```
package main;

import java.io.File;
import java.io.FileNotFoundException;
import java.io.FileOutputStream;
import java.io.OutputStream;

import org.apache.jena.query.Query;
import org.apache.jena.query.QueryExecution;
import org.apache.jena.query.QueryExecutionFactory;
import org.apache.jena.query.QueryFactory;
import org.apache.jena.rdf.model.Model;
import org.apache.jena.rdf.model.ModelFactory;
import org.apache.jena.rdf.model.Property;
import org.apache.jena.rdf.model.Resource;
import org.apache.log4j.BasicConfigurator;

public class Main {

    static final String inputFilePath = "C:\\Users\\An\\Desktop\\modelold.ttl";
    static Model modelold = ModelFactory.createDefaultModel().read(inputFilePath);


    public static void main(String args[]) throws FileNotFoundException
    {
        BasicConfigurator.configure();
        Model linking = ModelFactory.createDefaultModel();
        setlinkssaref();
        setlinkssensordescription();
        setlinkssensordata();
        Model model = createLinks(linking, modelold);
        //write the model into a file
        OutputStream out = new FileOutputStream(new File("D:\\data
file\\newmodel.ttl"));
        model.write(out, "TURTLE");

    }

    //method to link saref to geosensor
```

```
private static void setlinkssaref() {
    Model addition= ModelFactory.createDefaultModel();

    String query0 =
            "prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>\n" +
            "prefix GS: <http://purl.org/net/Geosensor#>\n" +
            "prefix saref: <https://w3id.org/saref#>\n"   +
            "\n" +
            "CONSTRUCT \n" +
                "  { GS:Geosensor  rdfs:subClassOf saref:Device.  }\n" +
            "WHERE { } ";
    Query setsubclassof = QueryFactory.create(query0);
    QueryExecution qe=QueryExecutionFactory.create(setsubclassof, modelold);
    addition.add(qe.execConstruct());
    modelold.add(addition);


}

private static void setlinkssensordata() {
    Model addition=ModelFactory.createDefaultModel();
    //through ground sensor link DHD to geosensor
    String query1 =
            "prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>\n" +
            "prefix DHD: <http://purl.org/net/DHD#>\n" +
            "prefix GS: <http://purl.org/net/Geosensor#>\n" +
            "\n" +
            "CONSTRUCT\n" +
            "  {  ?DHD  DHD:accomodate ?GS\n  "+
            "  }\n" +
            "WHERE\n"  +
            "  {  ?DHD DHD:hostgroundsettlementsensor ?sensor.\n" +
            "     ?GS  rdfs:label        ?sensor.\n" +
            "   }   ";
    org.apache.jena.query.Query groundsettlement = QueryFactory.create(query1);
    QueryExecution qe=QueryExecutionFactory.create(groundsettlement, modelold);
    addition.add(qe.execConstruct());
    //through water sensor link DHD to geosensor
    String query2 =
            "prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>\n" +
            "prefix DHD: <http://purl.org/net/DHD#>\n" +
            "prefix GS: <http://purl.org/net/Geosensor#>\n" +
            "\n" +
            "CONSTRUCT\n" +
```

```
                " {  ?DHD  DHD:accommodate ?GS\n  "+
                "  }\n" +
                "WHERE\n"  +
                " {  ?DHD DHD:hostwaterlevelsensor ?sensor.\n" +
                "     ?GS  rdfs:label        ?sensor.\n" +
                "   }   ";
        Query waterlevel = QueryFactory.create(query2);
        qe=QueryExecutionFactory.create(waterlevel, modelold);
        addition.add(qe.execConstruct());
        modelold.add(addition);

    }



    private static void setlinkssensordescription() {
        Model addition=ModelFactory.createDefaultModel();
        //through ground settlement sensor code link  DHD to SD
        String query3 =
            "prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>\n" +
            "prefix DHD: <http://purl.org/net/DHD#>\n" +
            "prefix SD: <http://purl.org/net/SD#>\n" +
            "\n" +
            "CONSTRUCT\n" +
            " {  ?DHD  DHD:issameas ?SD\n  "+
            "  }\n" +
            "WHERE\n"  +
            " {  ?DHD DHD:hostgroundsettlementsensor ?sensor.\n" +
            "     ?SD  SD:hassensorcode        ?sensor.\n" +
            "   }   ";

        Query addgroundsensordescription = QueryFactory.create(query3);
        QueryExecution qe=QueryExecutionFactory.create(addgroundsensordescription,
modelold);
        addition.add(qe.execConstruct());
        //through water level sensor code link DHD to SD
        String query4 =
            "prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>\n" +
            "prefix DHD: <http://purl.org/net/DHD#>\n" +
            "prefix SD: <http://purl.org/net/SD#>\n" +
            "\n" +
            "CONSTRUCT\n" +
            " {  ?DHD  DHD:isameas ?SD  }\n" +
            "WHERE\n"  +
```

```
            "  {   ?DHD DHD:hostwaterlevelsensor ?sensor.\n" +
            "      ?SD  SD:hassensorcode        ?sensor.\n" +
            "   }   ";

            Query addwatersensordescription = QueryFactory.create(query4);
            qe=QueryExecutionFactory.create(addwatersensordescription, modelold);
            addition.add(qe.execConstruct());
            modelold.add(addition);
        }

    /*  the linking process for drill hole link to building element is repetitive.
     since such links are assumed to verify the designed ontology, there is no direct
file indicates the links among them.
 so it is not designed like previous linking process using loops to link.*/
    private static Model createLinks(Model linking, Model modelold) {
        //Define linking properties
        String DHD = "http://purl.org/net/DHD#";
        String inst = "http://linkedbuildingdata.net/ifc/resources20170209_211457/";
        Property sensingelementground = linking.createProperty(DHD,
"sensingelementground");
        Property sensingelementwater = linking.createProperty(DHD,
"sensingelementwater");
        //DHD set links of DrillHole JK1

        Resource DrillHoleJK1 = linking.createResource(DHD+"2");
        Resource buildingelementW1 =
linking.createResource(inst+"IfcIdentifier_1954319");
        Resource buildingelementSW1 =
linking.createResource(inst+"IfcIdentifier_777524");
        DrillHoleJK1.addProperty(sensingelementground,buildingelementW1);
        DrillHoleJK1.addProperty(sensingelementwater,buildingelementSW1);
        //DHD set links of DrillHole JK2
        Resource DrillHoleJK2 = linking.createResource(DHD+"3");
        Resource buildingelementW2 =
linking.createResource(inst+"IfcIdentifier_1954030");
        Resource buildingelementSW2 =
linking.createResource(inst+"IfcIdentifier_777779");
        DrillHoleJK2.addProperty(sensingelementground,buildingelementW2);
        DrillHoleJK2.addProperty(sensingelementwater,buildingelementSW2);
        //DHD set links of DrillHole JK3
        Resource DrillHoleJK3 = linking.createResource(DHD+"4");
        Resource buildingelementW3 =
linking.createResource(inst+"IfcIdentifier_1954270");
        Resource buildingelementSW3 =
```

```
linking.createResource(inst+"IfcIdentifier_778304");
        DrillHoleJK3.addProperty(sensingelementground,buildingelementW3);
        DrillHoleJK3.addProperty(sensingelementwater,buildingelementSW3);
        //DHD set links of DrillHole JK4
        Resource DrillHoleJK4 = linking.createResource(DHD+"5");
        Resource buildingelementW4 =
linking.createResource(inst+"IfcIdentifier_1954285");
        Resource buildingelementSW4 =
linking.createResource(inst+"IfcIdentifier_786822");
        DrillHoleJK4.addProperty(sensingelementground,buildingelementW4);
        DrillHoleJK4.addProperty(sensingelementwater,buildingelementSW4);
        //DHD set links of DrillHole JK5
        Resource DrillHoleJK5 = linking.createResource(DHD+"6");
        Resource buildingelementW5 =
linking.createResource(inst+"IfcIdentifier_1954303");
        Resource buildingelementSW5 =
linking.createResource(inst+"IfcIdentifier_775631");
        DrillHoleJK5.addProperty(sensingelementground,buildingelementW5);
        DrillHoleJK5.addProperty(sensingelementwater,buildingelementSW5);
        //DHD set links of DrillHole JK6
        Resource DrillHoleJK6 = linking.createResource(DHD+"7");
        Resource buildingelementW6 =
linking.createResource(inst+"IfcIdentifier_1954319");
        Resource buildingelementSW6 =
linking.createResource(inst+"IfcIdentifier_775901");
        DrillHoleJK6.addProperty(sensingelementground,buildingelementW6);
        DrillHoleJK6.addProperty(sensingelementwater,buildingelementSW6);
        //DHD set links of DrillHole JK7
        Resource DrillHoleJK7 = linking.createResource(DHD+"8");
        Resource buildingelementW7 =
linking.createResource(inst+"IfcIdentifier_1954334");
        Resource buildingelementSW7 =
linking.createResource(inst+"IfcIdentifier_776097");
        DrillHoleJK7.addProperty(sensingelementground,buildingelementW7);
        DrillHoleJK7.addProperty(sensingelementwater,buildingelementSW7);
        //DHD set links of DrillHole JK8
        Resource DrillHoleJK8 = linking.createResource(DHD+"9");
        Resource buildingelementW8 =
linking.createResource(inst+"IfcIdentifier_1954348");
        Resource buildingelementSW8 =
linking.createResource(inst+"IfcIdentifier_776143");
        DrillHoleJK8.addProperty(sensingelementground,buildingelementW8);
        DrillHoleJK8.addProperty(sensingelementwater,buildingelementSW8);
        //DHD set links of DrillHole JK9
```

```
        Resource DrillHoleJK9 = linking.createResource(DHD+"10");
        Resource buildingelementW9 =
linking.createResource(inst+"IfcIdentifier_1954360");
        Resource buildingelementSW9 =
linking.createResource(inst+"IfcIdentifier_776443");
        DrillHoleJK9.addProperty(sensingelementground,buildingelementW9);
        DrillHoleJK9.addProperty(sensingelementwater,buildingelementSW9);
        //DHD set links of DrillHole JK10
        Resource DrillHoleJK10 = linking.createResource(DHD+"11");
        Resource buildingelementW10 =
linking.createResource(inst+"IfcIdentifier_1954375");
        Resource buildingelementSW10 =
linking.createResource(inst+"IfcIdentifier_776702");
        DrillHoleJK10.addProperty(sensingelementground,buildingelementW10);
        DrillHoleJK10.addProperty(sensingelementwater,buildingelementSW10);
        //DHD set links of DrillHole JK11
        Resource DrillHoleJK11 = linking.createResource(DHD+"12");
        Resource buildingelementW11 =
linking.createResource(inst+"IfcIdentifier_1954391");
        Resource buildingelementSW11 =
linking.createResource(inst+"IfcIdentifier_776894");
        DrillHoleJK11.addProperty(sensingelementground,buildingelementW11);
        DrillHoleJK11.addProperty(sensingelementwater,buildingelementSW11);
        //DHD set links of DrillHole JK12
        Resource DrillHoleJK12 = linking.createResource(DHD+"13");
        Resource buildingelementW12 =
linking.createResource(inst+"IfcIdentifier_1954407");
        Resource buildingelementSW12 =
linking.createResource(inst+"IfcIdentifier_777150");
        DrillHoleJK12.addProperty(sensingelementground,buildingelementW12);
        DrillHoleJK12.addProperty(sensingelementwater,buildingelementSW12);
        //DHD set links of DrillHole JK13
        Resource DrillHoleJK13 = linking.createResource(DHD+"14");
        Resource buildingelementW13 =
linking.createResource(inst+"IfcIdentifier_1954030");
        Resource buildingelementSW13 =
linking.createResource(inst+"IfcIdentifier_778351");
        DrillHoleJK13.addProperty(sensingelementwater,buildingelementW13);
        DrillHoleJK13.addProperty(sensingelementwater,buildingelementSW13);
        //DHD set links of DrillHole JK14
        Resource DrillHoleJK14 = linking.createResource(DHD+"15");
        Resource buildingelementW14 =
linking.createResource(inst+"IfcIdentifier_1954052");
        Resource buildingelementSW14 =
```

```
linking.createResource(inst+"IfcIdentifier_777478");
        DrillHoleJK14.addProperty(sensingelementground,buildingelementW14);
        DrillHoleJK14.addProperty(sensingelementwater,buildingelementSW14);
        //DHD set links of DrillHole JK15
        Resource DrillHoleJK15 = linking.createResource(DHD+"16");
        Resource buildingelementW15 =
linking.createResource(inst+"IfcIdentifier_1954068");
        Resource buildingelementSW15 =
linking.createResource(inst+"IfcIdentifier_777981");
        DrillHoleJK15.addProperty(sensingelementground,buildingelementW15);
        DrillHoleJK15.addProperty(sensingelementwater,buildingelementSW15);
        //DHD set links of DrillHole JK16
        Resource DrillHoleJK16 = linking.createResource(DHD+"17");
        Resource buildingelementW16 =
linking.createResource(inst+"IfcIdentifier_1954083");
        Resource buildingelementSW16 =
linking.createResource(inst+"IfcIdentifier_778351");
        DrillHoleJK16.addProperty(sensingelementground,buildingelementW16);
        DrillHoleJK16.addProperty(sensingelementwater,buildingelementSW16);
        //DHD set links of DrillHole JK17
        Resource DrillHoleJK17 = linking.createResource(DHD+"18");
        Resource buildingelementW17 =
linking.createResource(inst+"IfcIdentifier_1954100");
        Resource buildingelementSW17 =
linking.createResource(inst+"IfcIdentifier_778396");
        DrillHoleJK17.addProperty(sensingelementground,buildingelementW17);
        DrillHoleJK17.addProperty(sensingelementwater,buildingelementSW17);
        //DHD set links of DrillHole JK18
        Resource DrillHoleJK18 = linking.createResource(DHD+"19");
        Resource buildingelementW18 =
linking.createResource(inst+"IfcIdentifier_1954111");
        Resource buildingelementSW18 =
linking.createResource(inst+"IfcIdentifier_775677");
        DrillHoleJK18.addProperty(sensingelementground,buildingelementW18);
        DrillHoleJK18.addProperty(sensingelementwater,buildingelementSW18);
        //DHD set links of DrillHole ZK2
        Resource DrillHoleZK2 = linking.createResource(DHD+"20");
        Resource buildingelementW19 =
linking.createResource(inst+"IfcIdentifier_1954125");
        DrillHoleZK2.addProperty(sensingelementground,buildingelementW19);
        //DHD set links of DrillHole ZK3
        Resource DrillHoleZK3 = linking.createResource(DHD+"21");
        Resource buildingelementW20 =
linking.createResource(inst+"IfcIdentifier_1954140");
```

```
        DrillHoleZK3.addProperty(sensingelementground,buildingelementW20);
        //DHD set links of DrillHole ZK4
        Resource DrillHoleZK4 = linking.createResource(DHD+"22");
        Resource buildingelementW21 =
linking.createResource(inst+"IfcIdentifier_1954154");
        DrillHoleZK4.addProperty(sensingelementground,buildingelementW21);
        //DHD set links of DrillHole ZK5
        Resource DrillHoleZK5 = linking.createResource(DHD+"23");
        Resource buildingelementW22 =
linking.createResource(inst+"IfcIdentifier_1954431");
        DrillHoleZK5.addProperty(sensingelementground,buildingelementW22);
        //DHD set links of DrillHole ZK6
        Resource DrillHoleZK6 = linking.createResource(DHD+"24");
        Resource buildingelementW23 =
linking.createResource(inst+"IfcIdentifier_1954464");
        DrillHoleZK6.addProperty(sensingelementground,buildingelementW23);
        //DHD set links of DrillHole ZK7
        Resource DrillHoleZK7 = linking.createResource(DHD+"25");
        Resource buildingelementW24 =
linking.createResource(inst+"IfcIdentifier_1954443");
        DrillHoleZK7.addProperty(sensingelementground,buildingelementW24);
        //DHD set links of DrillHole ZK8
        Resource DrillHoleZK8 = linking.createResource(DHD+"26");
        Resource buildingelementW25 =
linking.createResource(inst+"IfcIdentifier_786625");
        DrillHoleZK8.addProperty(sensingelementground,buildingelementW25);
        //DHD set links of DrillHole ZK9
        Resource DrillHoleZK9 = linking.createResource(DHD+"27");
        Resource buildingelementW26 =
linking.createResource(inst+"IfcIdentifier_1954177");
        DrillHoleZK9.addProperty(sensingelementground,buildingelementW26);
        //DHD set links of DrillHole ZK10
        Resource DrillHoleZK10 = linking.createResource(DHD+"28");
        Resource buildingelementW27 =
linking.createResource(inst+"IfcIdentifier_1954189");
        DrillHoleZK10.addProperty(sensingelementground,buildingelementW27);
        //DHD set links of DrillHole ZK11
        Resource DrillHoleZK11 = linking.createResource(DHD+"29");
        Resource buildingelementW28 =
linking.createResource(inst+"IfcIdentifier_1954204");
        DrillHoleZK11.addProperty(sensingelementground,buildingelementW28);
        //DHD set links of DrillHole ZK12
        Resource DrillHoleZK12 = linking.createResource(DHD+"30");
        Resource buildingelementW29 =
```

```
linking.createResource(inst+"IfcIdentifier_1954219");
        DrillHoleZK12.addProperty(sensingelementground,buildingelementW29);
        //DHD set links of DrillHole ZK13
        Resource DrillHoleZK13 = linking.createResource(DHD+"31");
        Resource buildingelementW30 =
linking.createResource(inst+"IfcIdentifier_1954236");
        DrillHoleZK13.addProperty(sensingelementground,buildingelementW30);
        //DHD set links of DrillHole ZK14
        Resource DrillHoleZK14 = linking.createResource(DHD+"32");
        Resource buildingelementW31 =
linking.createResource(inst+"IfcIdentifier_1954252");
        DrillHoleZK14.addProperty(sensingelementground,buildingelementW31);

        Model model = modelold.union(linking);
        return model;

    }


}
```

## Appendix H coordinates system converter Java code

**Coverter from North east down system to Geocentric rectangular system**

```
package Coordinateconverter;

import java.text.DecimalFormat;
import java.util.*;

public class northeastdowntocartersian {
    static double a = 6378245.0;
    static double e2 = 0.00669342162297;
    static double PI = 3.1415926535897323;

    public static void main(String[] args) {
        BLH_XYZ();
    }

    public static void BLH_XYZ() {

        double B, L, H, N, W, d, f, m, X, Y, Z;

        System.out.println("Please input Geodetic coordinates (like: 30-40-50)");
        Scanner scanner1 = new Scanner(System.in);
        Scanner LScanner = new Scanner(scanner1.next());
        LScanner.useDelimiter("-");
        scanner1.useDelimiter("-");
        d = LScanner.nextDouble();
        f = LScanner.nextDouble();
        m = LScanner.nextDouble();
        L = RAD(d, f, m);
        System.out.println("longitude: L=" + L);

        System.out.println("Please input Geodetic coordinates (like: 30-40-50)");
        Scanner scanner2 = new Scanner(System.in);
        Scanner BScanner = new Scanner(scanner2.next());
        BScanner.useDelimiter("-");
        d = BScanner.nextDouble();
        f = BScanner.nextDouble();
        m = BScanner.nextDouble();
        B = RAD(d, f, m);
        System.out.println("latitude: B=" + B);
```

```
        Scanner HScanner = new Scanner(System.in);
        System.out.println("Please input H value:");
        H = HScanner.nextDouble();
        System.out.println("height: H=" + H);

        scanner1.close();
        scanner2.close();
        LScanner.close();
        BScanner.close();
        HScanner.close();

        W = Math.sqrt(1 - e2 * Math.sin(B) * Math.sin(B));
        N = a / W;
        X = (N + H) * Math.cos(B) * Math.cos(L);
        Y = (N + H) * Math.cos(B) * Math.sin(L);
        Z = (N * (1 - e2) + H) * Math.sin(B);

        DecimalFormat df = new DecimalFormat("0.00");
        System.out.println("The Cartesian coordinates X=" + df.format(X) + ",Y=" +
df.format(Y) + ",Z=" + df.format(Z));
    }

    public static double RAD(double d, double f, double m) {
        double e;
        double sign = (d < 0.0) ? -1.0 : 1.0;
        if (d == 0) {
            sign = (f < 0.0) ? -1.0 : 1.0;
            if (f == 0) {
                sign = (m < 0.0) ? -1.0 : 1.0;
            }
        }
        if (d < 0) {
            d = d * (-1.0);
        }
        if (f < 0) {
            f = f * (-1.0);
        }
        if (m < 0) {
            m = m * (-1.0);
        }
        e = sign * (d * 3600 + f * 60 + m) * PI / (3600 * 180);
        return e;
    }
}
```

**Converter from geocentric rectangular system to north east down system**

```
package Coordinateconverter;

import java.text.DecimalFormat;
import java.util.*;

public class cartersiantonortheastdownconverter {
    static double a = 6378245.0;
    static double e2 = 0.00669342162297;
    static double PI = 3.1415926535897323;

    public static void main(String[] args) {
        XYZ_BLH();
    }

    public static void XYZ_BLH() {
        double B, L, H, N, W, X, Y, Z, tgB0, tgB1;
        System.out.println("Please input Cartesian coordinates! ! ! ");
        Scanner scanner1 = new Scanner(System.in);
        System.out.print("X=");
        X = scanner1.nextDouble();

        Scanner scanner2 = new Scanner(System.in);
        System.out.print("Y=");
        Y = scanner2.nextDouble();

        Scanner scanner3 = new Scanner(System.in);
        System.out.print("Z=");
        Z = scanner3.nextDouble();

        scanner1.close();
        scanner2.close();
        scanner3.close();

        L = Math.atan(Y / X);
        System.out.println("longitude: L="+L);
        RBD(L);
        System.out.println("");
        tgB0 = Z / Math.sqrt(X * X + Y * Y);
        tgB1 = (1 / Math.sqrt(X * X + Y * Y)) * (Z + a * e2 * tgB0 / Math.sqrt(1 + tgB0
```

```
* tgB0 - e2 * tgB0 * tgB0));
         (Math.abs(tgB0 - tgB1) > 5 * Math.pow(10, -10)) {
            tgB0 = tgB1;
            tgB1 = (1 / Math.sqrt(X * X + Y * Y)) * (Z + a * e2 * tgB0 / Math.sqrt(1
+ tgB0 * tgB0 - e2 * tgB0 * tgB0));
        }
        B = Math.atan(tgB1);
        System.out.println("latitude: B="+B);
        RBD(B);
        System.out.println("");
        W = Math.sqrt(1 - e2 * Math.sin(B) * Math.sin(B));
        N = a / W;
        H = Math.sqrt(X * X + Y * Y) / Math.cos(B) - N;

        DecimalFormat df = new DecimalFormat("0.00");
        System.err.println("height: H=" + df.format(H));
    }

    public static void RBD(double hd) {
        int t;
        int d;
        int f;
        double m;
        double sign = (hd < 0.0) ? -1.0 : 1.0;
        if (hd < 0) {
            hd = Math.abs(hd);
        }
        hd = hd * 3600 * 180 / PI;
        t = (int) (hd / 3600);
        d = (int) (sign * t);
        hd = hd - t * 3600;
        f = (int) (hd / 60);
        m = hd - f * 60;
        DecimalFormat df = new DecimalFormat("0.00");
        System.out.println("The Cartesian coordinates d=" + d + ",f=" + f + ",m=" +
df.format(m));
        //System.out.printf("%d'%d'%lf'\n", d, f, m);
    }
}
```

## Appendix I SPAQL code

Under the dataset /querytest

**sensor value query**

```
PREFIX rdf:     <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs:  <http://www.w3.org/2000/01/rdf-schema#>
PREFIX DHD:     <http://purl.org/net/DHD#>
PREFIX GS:    <http://purl.org/net/Geosensor#>
PREFIX inst:
   <http://linkedbuildingdata.net/ifc/resources20170209_211457/>

SELECT ?drillholecode ?groundsensor ?value_ground ?sensingelementg
round
?watersensor ?value_water ?sensingelementwater

WHERE {
   ?dhd DHD:hasdrillholecode ?drillholecode.
   ?dhd  DHD:sensingelementground ?sensingelementground.
   ?dhd  DHD:hostgroundsettlementsensor  ?groundsensor.
   ?record rdf:type ?sensorclass.
   ?sensorclass rdfs:label ?groundsensor.
   ?record GS:hasmeasruingdate "2016/1/7".
   ?record GS:hasmeasuringvalue ?value_ground.
   OPTIONAL{
      ?dhd  DHD:sensingelementwater ?sensingelementwater.
      ?dhd  DHD:hostwaterlevelsensor  ?watersensor.
      ?record2 rdf:type ?sensorclass2.
      ?sensorclass2 rdfs:label ?watersensor.
      ?record2 GS:hasmeasruingdate "2016/1/7".
      ?record2 GS:hasmeasuringvalue ?value_water.
   }
}
```

**DHD data query (the query block is for designers to reuse existing facilities)**

```
PREFIX DHD:      <http://purl.org/net/DHD#>

SELECT ?drillholecode  ?coordinateX ?coordinateY ?elevation
    ?groundsensor   ?watersensor

WHERE {
    ?dhd   DHD:hasdrillholecode   ?drillholecode.
    ?dhd   DHD:hascoordinateX     ?coordinateX.
    ?dhd   DHD:hascoordinateY     ?coordinateY.
    ?dhd   DHD:haselevation       ?elevation.
    OPTIONAL{
        ?dhd   DHD:hostgroundsettlementsensor  ?groundsensor.
        ?dhd   DHD:hostwaterlevelsensor  ?watersensor.
    }
}
```

**Building element coordinates query**

```
prefix BE:    <http://purl.org/net/buildingelement#>

SELECT  ?hasGUID ?hasTAG  ?hasLatitude ?hasLongitude
WHERE {
  ?subject BE:hasGUID ?hasGUID.
  ?subject BE:hasTAG  ?hasTAG.
  ?subject BE:hasLatitude ?hasLatitude.
  ?subject BE:hasLongitude ?hasLongitude.
  filter (contains(?hasLatitude,"39 4")||contains(?hasLatitude,"39 5"))
  filter(contains(?hasLongitude,"116 2")||contains(?hasLongitude,"116
3"))
}
```

## Appendix J query result

Table J.1 complete query result for designers to use

| "drillholecode" | "coordinateX" | "coordinateY" | "elevation" | "groundsensorcode" | "watersensorcode" |
|---|---|---|---|---|---|
| "ZK11" | "-3996.25" | "-17292.37" | "6" | "W28" | |
| "ZK6" | "-3137.5" | "-18015.98" | "4.24" | "W23" | |
| "JK8" | "-3209.66" | "-17928.79" | "4.11" | "W8" | "SW8" |
| "JK3" | "-2670.12" | "-18181.11" | "4.66" | "W3" | "SW3" |
| "BC2" | "-4301.4" | "-17025.33" | "4.36" | | |
| "JK14" | "-4215.9" | "-17048.6" | "4.36" | "W14" | "SW14" |
| "ZK13" | "-4172.51" | "-17159.85" | "4.14" | "W30" | |
| "JK9" | "-3423.49" | "-17757.52" | "4.6" | "W9" | "SW9" |
| "ZK9" | "-3633.43" | "-17589.34" | "3.99" | "W26" | |
| "ZK4" | "-2758.11" | "-18285.66" | "3.98" | "W21" | |
| "JK6" | "-2923.07" | "-18148.72" | "4.14" | "W6" | "SW6" |
| "JK1" | "-2537.31" | "-17964.77" | "5.28" | "W1" | "SW1" |
| "JK17" | "-4610.21" | "-16826.54" | "4.52" | "W17" | "SW17" |
| "ZK16" | "-4647.25" | "-16763.69" | "4.33" | "W33" | |
| "JK12" | "-4019.27" | "-17267.27" | "5.35" | "W12" | "SW12" |
| "ZK7" | "-3331.87" | "-17863.45" | "4.79" | "W24" | |
| "ZK2" | "-2594.04" | "-18125.73" | "4.18" | "W19" | |
| "JK4" | "-2854.76" | "-18240.59" | "4.43" | "W4" | "SW4" |
| "SK1" | "-4524.08" | "-16828.28" | "4.18" | | |
| "JK15" | "-4360.92" | "-16950.17" | "3.88" | "W15" | "SW15" |
| "ZK14" | "-4302.4" | "-17029.33" | "5.21" | "W31" | |
| "JK10" | "-3731.89" | "-17544.18" | "4.41" | "W10" | "SW10" |
| "ZK10" | "-3812.05" | "-17445.37" | "4.01" | "W27" | |
| "ZK5" | "-2942.59" | "-18186.07" | "4.16" | "W22" | |
| "JK7" | "-3018.8" | "-18082.38" | "4.2" | "W7" | "SW7" |
| "JK2" | "-2605.77" | "-18022.74" | "5.24" | "W2" | "SW2" |
| "JK18" | "-3875.7" | "-17279.33" | "3.96" | "W18" | "SW18" |
| "BC1" | "-4173.51" | "-17157.85" | "4.18" | | |
| "JK13" | "-4073.81" | "-17202.59" | "4.43" | "W13" | "SW13" |
| "ZK12" | "-4040.96" | "-17293.49" | "4.87" | "W29" | |
| "ZK8" | "-3533.68" | "-17708.04" | "4.52" | "W25" | |
| "ZK3" | "-2652.8" | "-18283" | "4.35" | "W20" | |
| "JK5" | "-2909.48" | "-18171.26" | "4.12" | "W5" | "SW5" |
| "SK2" | "-4644.25" | "-16769.69" | "4.36" | | |
| "JK16" | "-4443.99" | "-16924.7" | "5.04" | "W16" | "SW16" |
| "ZK15" | "-4526.08" | "-16827.28" | "4.32" | "W32" | |
| "JK11" | "-3922.46" | "-17393.7" | "3.87" | "W11" | "SW11" |

Table J.2 complete converted coordiantes also prepared for designers' reuse

| "DrillHoleCode" | Global X | Global Y | Lat | Lon |
|---|---|---|---|---|
| "JK1" | -2180728.991 | -4386832.946 | 39 54 54.1184775 N | 116 25 56.3894595 W |
| "JK2" | -2180729.675 | -4386833.526 | 39 54 54.1013389 N | 116 25 56.4043774 W |
| "JK3" | -2180730.319 | -4386835.109 | 39 54 54.0658863 N | 116 25 56.3989889 W |
| "JK4" | -2180732.165 | -4386835.704 | 39 54 54.0377077 N | 116 25 56.4574356 W |
| "JK5" | -2180732.712 | -4386835.011 | 39 54 54.0455518 N | 116 25 56.491047 W |
| "JK6" | -2180732.848 | -4386834.786 | 39 54 54.0484838 N | 116 25 56.5003915 W |
| "JK7" | -2180733.806 | -4386834.122 | 39 54 54.0519817 N | 116 25 56.5489549 W |
| "JK8" | -2180735.714 | -4386832.586 | 39 54 54.2268942 N | 116 25 56.6496786 W |
| "JK14" | -2180745.777 | -4386823.784 | 39 54 54.1337064 N | 116 25 57.1940442 W |
| "ZK10" | -2180741.738 | -4386827.752 | 39 54 54.0971916 N | 116 25 56.9673961 W |
| "JK9" | -2180737.852 | -4386830.874 | 39 54 54.0750194 N | 116 25 56.7623724 W |
| "ZK5" | -2180733.043 | -4386835.159 | 39 54 54.0397296 N | 116 25 56.5007526 W |
| "BC2" | -2180746.632 | -4386823.552 | 39 54 54.1301105 N | 116 25 57.2306278 W |
| "ZK13" | -2180745.343 | -4386824.897 | 39 54 54.116992 N | 116 25 57.1568214 W |
| "JK18" | -2180742.375 | -4386826.092 | 39 54 54.1222159 N | 116 25 57.0225244 W |
| "JK13" | -2180744.356 | -4386825.324 | 39 54 54.1181777 N | 116 25 57.1116064 W |
| "ZK9" | -2180739.952 | -4386829.192 | 39 54 54.0869057 N | 116 25 56.8730713 W |
| "ZK4" | -2180731.199 | -4386836.155 | 39 54 54.0382518 N | 116 25 56.4125626 W |
| "BC1" | -2180745.353 | -4386824.877 | 39 54 54.1172719 N | 116 25 57.1575733 W |
| "ZK12" | -2180744.027 | -4386826.233 | 39 54 54.1042911 N | 116 25 57.0821658 W |
| "JK17" | -2180749.72 | -4386821.564 | 39 54 54.1385476 | 116 25 |

| | | | | |
|---|---|---|---|---|
| | | | N | 57.3843116 W |
| "JK12" | -2180743.81 | -4386825.971 | 39 54 54.1111813 N | 116 25 57.0788948 W |
| "ZK8" | -2180738.954 | -4386830.379 | 39 54 54.0740356 N | 116 25 56.8131976 W |
| "ZK3" | -2180730.146 | -4386836.128 | 39 54 54.0485059 N | 116 25 56.3733683 W |
| "ZK16" | -2180750.09 | -4386820.935 | 39 54 54.1468386 N | 116 25 57.4100503 W |
| "JK16" | -2180748.057 | -4386822.545 | 39 54 54.1356733 N | 116 25 57.3032268 W |
| "JK11" | -2180742.842 | -4386827.235 | 39 54 54.096599 N | 116 25 57.018709 W |
| "ZK7" | -2180736.936 | -4386831.933 | 39 54 54.0637744 N | 116 25 56.7079893 W |
| "SK2" | -2180750.06 | -4386820.995 | 39 54 54.1459987 N | 116 25 57.4077947 W |
| "ZK2" | -2180729.558 | -4386834.556 | 39 54 54.083235 N | 116 25 56.3806619 W |
| "ZK15" | -2180748.878 | -4386821.571 | 39 54 54.1462145 N | 116 25 57.3524352 W |
| "JK15" | -2180747.227 | -4386822.8 | 39 54 54.1386092 N | 116 25 57.2671547 W |
| "ZK11" | -2180743.58 | -4386826.222 | 39 54 54.1086354 N | 116 25 57.065519 W |
| "JK10" | -2180740.936 | -4386828.74 | 39 54 54.0862135 N | 116 25 56.9186417 W |
| "ZK6" | -2180734.993 | -4386833.458 | 39 54 54.0533589 N | 116 25 56.6061522 W |
| "SK1" | -2180748.858 | -4386821.581 | 39 54 54.1462135 N | 116 25 57.3514938 W |
| "ZK14" | -2180746.642 | -4386823.592 | 39 54 54.1292728 N | 116 25 57.2302551 W |

| "drillhol ecode" | "ground sensor" | "value_ ground" | "sensingelementground" | "water sensor" | "value_ water" | "sensingelementwater" | "ground sensor" |
|---|---|---|---|---|---|---|---|
| "ZK13" | "W30" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_1954236" | | | | "W30" |
| "JK17" | "W17" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_1954100" | "SW17 " | "-2.196 " | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_778396" | "W17" |
| "ZK12" | "W29" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_1954219" | | | | "W29" |
| "JK3" | "W3" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_1954270" | "SW3" | "-3.43" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_778304" | "W3" |
| "ZK9" | "W26" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_1954177" | | | | "W26" |
| "ZK8" | "W25" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_786625" | | | | "W25" |
| "ZK6" | "W23" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_1954464" | | | | "W23" |
| "JK9" | "W9" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_1954360" | "SW9" | "-6.105 " | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_776443" | "W9" |
| "ZK2" | "W19" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_1954125" | | | | "W19" |
| "JK6" | "W6" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_1954319" | "SW6" | "null" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_775901" | "W6" |
| "JK5" | "W5" | "null" | "http://linkedbuildingdata.net/ifc/resources2 | "SW5" | "-2.55" | "http://linkedbuildingdata.net/ifc/resources2 0170209_211457/IfcIdentifier_775631" | "W5" |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0170209_211457/IfcIdentifier_1954303" | | | | |
| "JK12" | "W12" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954407" | "SW12" | "-4.346" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_777150" | "W12" |
| "JK18" | "W18" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954111" | "SW18" | "-1.962" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_775677" | "W18" |
| "JK11" | "W11" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954391" | "SW11" | "-5.213" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_776894" | "W11" |
| "JK16" | "W16" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954083" | "SW16" | "-3.01" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_778351" | "W16" |
| "JK2" | "W2" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954030" | "SW2" | "-1.99" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_777779" | "W2" |
| "JK15" | "W15" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954068" | "SW15" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_777981" | "W15" |
| "JK1" | "W1" | "0.2" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954319" | "SW1" | "-3.46" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_777524" | "W1" |
| "ZK7" | "W24" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954443" | | | | "W24" |
| "JK4" | "W4" | "0.5" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954285" | "SW4" | "-2.9" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_786822" | "W4" |
| "JK10" | "W10" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954375" | "SW10 | "-3.709 | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_776702" | "W10" |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | " | " | | |
| "ZK5" | "W22" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954431" | | | | "W22" |
| "JK8" | "W8" | "0.3" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954348" | "SW8" | "-2.921 " | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_776143" | "W8" |
| "JK14" | "W14" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954052" | "SW14 " | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_777478" | "W14" |
| "ZK11" | "W28" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954204" | | | | "W28" |
| "ZK14" | "W31" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954252" | | | | "W31" |
| "ZK10" | "W27" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954189" | | | | "W27" |
| "ZK4" | "W21" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954154" | | | | "W21" |
| "ZK3" | "W20" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954140" | | | | "W20" |
| "JK7" | "W7" | "null" | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_1954334" | "SW7" | "-6.345 " | "http://linkedbuildingdata.net/ifc/resources20170209_211457/IfcIdentifier_776097" | "W7" |

Appendix J.3 complete query result for sensor value

# Appendix K The whole set for all drill holes and their related structural elements

| Sensor Code | linked element Tag | according IfcIdentifier |
|---|---|---|
| SW1 | 491769 | 777524 |
| SW2 | 491968 | 777779 |
| SW3 | 492518 | 778304 |
| SW4 | 638657 | 786822 |
| SW5 | 490894 | 775631 |
| SW6 | 491003 | 775901 |
| SW7 | 491051 | 776097 |
| SW8 | 491079 | 776143 |
| SW9 | 491114 | 776443 |
| SW10 | 491242 | 776702 |
| SW11 | 491313 | 776894 |
| SW12 | 491367 | 777150 |
| SW13 | 492788 | 778351 |
| SW14 | 491539 | 777478 |
| SW15 | 492229 | 777981 |
| SW16 | 492788 | 778351 |
| SW17 | 492815 | 778396 |
| SW18 | 490939 | 775677 |
| W1 | 785900 | 1954319 |
| W2 | 643467 | 1954030 |
| W3 | 785894 | 1954270 |
| W4 | 785896 | 1954285 |
| W5 | 785898 | 1954303 |
| W6 | 785900 | 1954319 |
| W7 | 785902 | 1954334 |
| W8 | 785904 | 1954348 |
| W9 | 785906 | 1954360 |
| W10 | 785908 | 1954375 |
| W11 | 785910 | 1954391 |
| W12 | 785912 | 1954407 |
| W13 | 785831 | 1954030 |
| W14 | 785833 | 1954052 |
| W15 | 785835 | 1954068 |

| | | |
|---|---|---|
| W16 | 785837 | 1954083 |
| W17 | 785839 | 1954100 |
| W18 | 785841 | 1954111 |
| w19 | 785843 | 1954125 |
| W20 | 785845 | 1954140 |
| W21 | 785847 | 1954154 |
| W22 | 785914 | 1954431 |
| W23 | 785918 | 1954464 |
| W24 | 785916 | 1954443 |
| W25 | 631381 | 786625 |
| W26 | 785857 | 1954177 |
| W27 | 785859 | 1954189 |
| W28 | 785861 | 1954204 |
| W29 | 785863 | 1954219 |
| W30 | 785871 | 1954236 |
| W31 | 785873 | 1954252 |

## Appendix L python code to convert coordinates in IFC file.(source T.F.Krijnen)

```
import ifcopenshell
import ifcopenshell.geom
import numpy as np
import json

S = ifcopenshell.geom.settings()
S.set(S.USE_WORLD_COORDS, True)

def a2p(o,z,x):
    y = np.cross(z, x)
    r = np.eye(4)
    r[:-1,:-1] = x,y,z
    r[-1,:-1] = o
    return r.T

def axis2placement(plc):
    z = np.array(plc.Axis.DirectionRatios if plc.Axis else (0,0,1))
    x = np.array(plc.RefDirection.DirectionRatios if plc.RefDirection else
(1,0,0))
    o = plc.Location.Coordinates
    return a2p(o,z,x)

def local_placement(plc):
    if plc.PlacementRelTo is None:
        parent = np.eye(4)
    else:
        parent = local_placement(plc.PlacementRelTo)
    return np.dot(axis2placement(plc.RelativePlacement), parent)

f = ifcopenshell.open(r"Dongjingstation.ifc")

for w in f.by_type("IFCSLAB"):
    shp = ifcopenshell.geom.create_shape(S, w)
    positions = shp.geometry.verts

    ##continue

    print json.dumps(w, default=vars, indent=2)
    ##continue
    matrix = local_placement(w.ObjectPlacement)
```

```
pos = matrix.T[3][:-1]
print w
print pos
```

## Appendix M Sorted table for building elements' location

| GUID | TAG | X | Y | Z | Lat | Lon | Global X | Global Y |
|---|---|---|---|---|---|---|---|---|
| 0aS007Wh5 | 434485 | -73996.4 | 18410.2 | 4800 | 39 38 51. | 117 37 29 | -2295803 | -4368243 |
| 0CuGbA85T | 477227 | 18510.3 | -15577.3 | 1020 | 39 47 4.4 | 116 35 15 | -2203297 | -4402231 |
| 3sxEdn0Zv | 500357 | 5293.64 | -76077.3 | -10380 | 39 21 48. | 116 24 44 | -2216513 | -4462731 |
| 2s V3tIxF | 500836 | 14260.3 | -85310.6 | 4800 | 39 26 37. | 116 16 22 | -2207547 | -4471964 |
| 3$AndZntv | 520222 | -30221.4 | 5185.24 | -13436 | 39 39 51. | 117 12 9. | -2252028 | -4381468 |
| 3$AndZntv | 520293 | 95162.89 | 5072.74 | -13436 | 39 59 15. | 115 53 24 | -2126644 | -4381581 |
| 3$AndZntv | 521130 | -24444.4 | -10202.3 | -7502 | 39 38 31. | 117 3 41. | -2246251 | -4396856 |
| 1lH3Cc0iX | 523099 | 16643.64 | -78877.3 | -9130 | 39 23 11. | 116 16 51 | -2205163 | -4465531 |
| 1lH3Cc0iX | 523184 | 8506.14 | -78077.3 | -7430 | 39 22 54. | 116 22 8. | -2213301 | -4464731 |
| 1lH3Cc0iX | 523232 | 3521.31 | -77960.6 | -8980 | 39 21 32. | 116 25 15 | -2218286 | -4464614 |
| 1lH3Cc0iX | 523270 | 5293.63 | -76077.3 | -10380 | 39 21 48. | 116 24 44 | -2216513 | -4462731 |
| 2cABoXZ2D | 646380 | 16143.63 | -71327.3 | 0 | 39 29 11. | 116 19 28 | -2205663 | -4457981 |
| 2cABoXZ2D | 646573 | 16143.63 | -71327.3 | 4800 | 39 31 10. | 116 19 28 | -2205663 | -4457981 |
| 2gG5ILN 5 | 648315 | 18510.3 | -15577.3 | 4800 | 39 48 38. | 116 35 15 | -2203297 | -4402231 |
| | | | | | | | | |