FAIR Geotechnical data to support BIM for Underground Infrastructure

Mickaël Beaufils, N Hassan, C Galandrin, P Miraillet, B Le Hello, Isabelle Halfon

FAIR Geotechnical data to support BIM for Underground Infrastructure

M. Beaufils[1], N. Hassan[2], C. Galandrin[3], P. Miraillet[4], B. Le Hello[5] and I. Halfon[6]
[1]Direction des Infrastructures et Services Numériques, BRGM, Orléans, France
[2] Aménagements Linéaires et Structures, SETEC, Lyon, France
[3] Service Innovation Recherche et Développement, CAN, Mirmande, France
[4], Direction Ingénierie et Projets Nouveau Nucléaire / Direction Industrielle, EDF, Aix-en-Provence, France
[5] Business Unit Grands Ouvrages Eau Environnement et Energie, EGIS, Grenoble, France
[6] Direction des Risques et Préventions, BRGM, Orléans, France

E-mail: m.beaufils@brgm.fr

ABSTRACT:

In France, the MINnD Project aims at extending Building Information Modeling (BIM) capacities to describe infrastructures such as roads, bridges, railways, tunnels and geotechnics. The MINnD working group GT1-5 is dedicated to Geotechnics, especially in an underground infrastructure construction context. Such activity leads to the proposal of a conceptual data model and appropriate vocabularies to describe the geotechnical conditions. Those deliverables contribute to the specification of international standards for openBIM (as part of the buildingSmart International IFC Tunnel project) and in openGIS (Open Geospatial Consortium standards) in connection with existing practices (AFTES recommendation). MINnD GT1-5 then enables to organize the provision of geological and geotechnical data compliant with the FAIR principles (Findable, Accessible, Interoperable and Reusable). Such level of interoperability is necessary to envisage the definition of a Digital Twin of the environment of an Underground Infrastructure and its sustainable management.

KEYWORDS: Geotechnical data, Building Information Modeling, Data interchange, Interoperability

1. INTRODUCTION

Infrastructure projects are always a team work. Different actors get to be involved in the same project to play different and various roles, such as the entity in charge of design or the one in charge of execution. Even in the same entity, different contributors for different topics (geotechnical, structure, drainage, landscape..etc) participate at the same project. Also, a complete project study is always done via different stages over time, providing progressive level of details at each step.

In France for example, four stages of geotechnical studies workflow are applicable: mission G1 to G4, where G1 aims of getting the main project context (geological, hydrogeological and ground related risks) till G4 with the construction follow up. Different actors may be in charge at each study level.

At each step of a project, geotechnical data may be collected, analyzed and interpreted. In the current practice of typical projects, each actor has its own method of data analysis and structuration. For instance, the same geotechnical property may be called with different names (e.g. undrained cohesion / undrained shear strength) and may be measured with different methods (e.g. vane test / UU triaxial test / derived from correlation).

In addition, many geotechnical properties (as for example drained cohesion and friction angle) are not the direct result of a simple measurement but are derived from more or less complex tests, involving different specimens, intermediate values and an interpretation, that are worth to be traceable. Regarding the data exchange, the same type of data can be provided with various formats: pdf, spreadsheet, etc.

Such heterogeneity of formats is enforced by the existence of different softwares. For these reasons, geotechnical data are often not easily accessible and exchangeable between the different stakeholders of a given project, and also from a project to another one, and therefore are often used only once.

In addition, today the geotechnical model is becoming an essential part of the BIM model, especially for infrastructures like roads, bridges, railways, tunnels and underground projects. To be incorporated in a BIM model, it is essential that geotechnical properties and objects be clearly defined and described, and that their provenance (e.g measurement method or procedure) be tracked.

For these reasons, the geotechnical data exchange can be challenging and needs to develop interoperable formats, in order to avoid data loss and time consuming.

In 2016, FAIR principles have been introduced in order to describe the level of interoperability one user can have with numerical data. Four criteria were defined. They all together form the FAIR accronym.

- Findable: the capacity to discover existing data,
- Accessible: the capacity to get data,
- Interoperable: the capacity to understand the obtained data,
- Reusable: the capacity to exploit the data.

In practice, setting data that match those FAIR principles require to take care of data description (Interoperability and Reusability criteria) but also set additional components to make data Findable and Accessible. These prerogatives enable to define the order in which those criteria shall be taken into account.

This paper presents the actions and results from the French MINnD GT1-5 project for geotechnical data standardization. The focus is on the compliance with the FAIR principles and the processes followed to reach them. More than technical solutions, it also opens discussion on geotechnical data exchange and sharing, and the possible role that organizations like national geological surveys can play.

2. INTEROPERABLE

The question of data description is a key topic in science and other domain. Shared language and vocabularies are necessary to prevent from misunderstanding the information and its meaning.

Standardization mostly rely on the identification and definition of agreed concepts to be used for data description. Such activity shall be driven by the requirements of the domain (i.e. geotechnics) and current practices.

The data structuration proposal from MINnD is based on two main inspiration:

- The AFTES guidelines that introduces three books for the furniture of geotechnical data. Book A, B and C for respectively the factual data (i.e. investigations), the modeling of the environment of the infrastucture and finally the design and construction methods,
- The French NF P 94500 standard that define the geotechnical missions and the level of knowledge that is expected at each stage of the project.

It introduces a distinguo between two families of features: objects and observations & measurements. The first one being dedicated to real or modeled objects, the second for describing a property or value that has been observed or measured.

2.1 Object identification and data modeling

Identification of the relevant concepts to have in the data model was based on the study of existing models built by the members of the group and current data exchange. The idea was to be able to describe each element geotechnical engineers use to represent or document.

One key statement was the co-existence of multiple accepted representations for the same kind of models. This early statement lead the group to focus on setting a conceptual model that would enable different kind of representations for the same concepts. In other words, the idea was to be able to both describe and confront 2D cross-sections, 2D maps and 3D models relying on the same terminology.

A distinction has been made between what are called the "observation supports" from which geotechnical investigations are made, and the "interpreted objects" which encompasses all used features in order to create a ground model.

They are respectively associated to Book A for the first and Book B or C for the second.

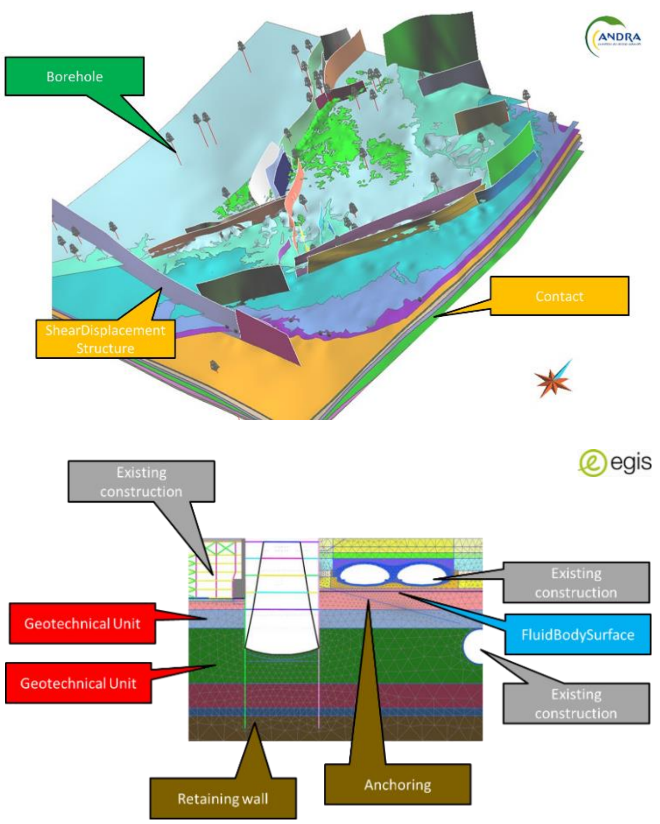

Figure 1 Identification of relevant concepts based on the study of the models made by the members. The one in brown are part of the solution and then are not addressed by the Geotechnical group.

In Book A, the focus is on the factual data or investigations. They can be either performed in-situ or through a proxy (ie. a sample that will be studied in a laboratory). This list covers all type of exploratory holes, such as cable percussion borehole and trial pit; in-situ analysis such as pressuremeter measurements; geophysics investigations like radar and geotechnical laboratory tests. The location of the test and the sampling location are important information to build a geomodel.

In Book B, which is dedicated to the geotechnical synthesis, the main elements are the components of the models, called the interpreted objects. The concept of a "Geotechnical Unit" for example, which is either a surface or a volume in which the mechanical behavior is modeled using the same values, is a fundamental concept for a geotechnical design, though it is not yet integrated in a standard.

Finally, Book C addresses the description of the designed solution. This is where objects describing the underground infrastructure (eg. bolts, tunnel sections) meet geotechnical information and recommendation.

Possible links can occur between different objects/elements, which should also be specified. For example, by specifying the link between a borehole and a layer, it could be always possible to identify the input data (borehole data, laboratory test results on a sample from this borehole), used in the analysis and affected to a certain soil layer.

In fact, an object does not only mean a singular numerical value, but also an overall context. By this way, designer can have easily a critical eye on data quality, which is very important in geotechnical design as it is not an exact science.

The figure below provides an overview of the observed supports and interpreted objects. Most of them are already defined in existing data models, especially from the ISO or the Open Geospatial Consortium (OGC). MINnD GT1-5 decided to reuse those existing concepts and look at the properties that enable to describe them.

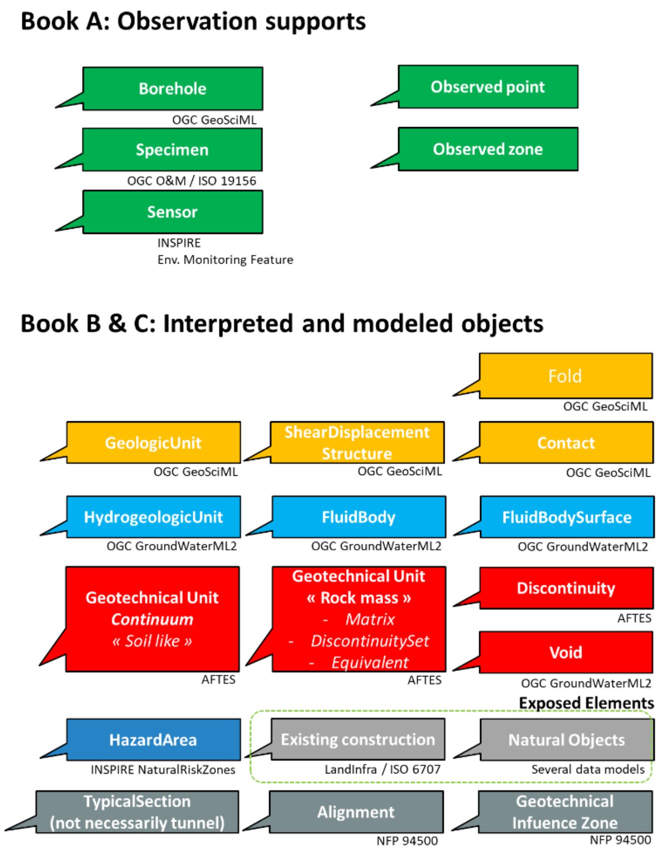

Figure 2 Identified concepts and their associated properties for geotechnical data description and exchange

2.2 Properties, methods and other semantics

Geotechnical Engineering addresses several domains including geology, hydrogeology, geochemistry or geophysics.

A same word can be associated to different meanings from a topic to another. Such differences may lead to misunderstanding that could lead to bad information transmission.

In order to find interoperability, each term that is used shall be clearly defined. When the word by itself is not explicit enough or might be associated to different meaning, one should able to refer to a description of it.

The MINnD GT1-5 work leads to the identification of several terms including:

- Observed properties: the characteristics that are determined (eg. shear strength, permeability),
- Methods and procedures: the processes and technics that enable to obtain data. This includes a large yet non exhaustive list of tests, analysis (generally associated to standards) or calculus that can be made and lead to the creation of result or knowledge,
- Units of measures: to be necessarily associated to numerical values.

In practice, the deliverable of that activity was a collection of spreadsheets that contain and organize all those terms, definitions and also the relationship between them. The final document was named Pro3, standing for Properties, Processus and Provenance.

It contains many references to existing standards or terminologies, such as the dictionary of geology, national and international standards, including Eurocodes and ISO.

3. REUSABLE

Using existing data, especially for other purposes than the one they were designed for is a very engaging act. It can only be done properly if the user has a sufficient knowledge or trust in the data or if he can access to the raw data.

3.1 Uncertainty expression and result contextualization

Uncertainty expression is a recurrent topic in geoscience and source of a lot of research. Several solutions have been designed to address it as depicted in Pérez-Díaz, L. et al (2020).

One targeted approach is to be able to qualify and quantify uncertainty. Technically the provision of such information would not be very different from expressing an observation or measurement. Yet, the main difficulty is concentrated on the description, i.e. qualification and quantification of the uncertainty itself, leading to a rare furniture of information regarding uncertainty expression.

As an alternative to explicit uncertainty expression, MINnD GT1-5 worked on the capacity to give the user the context in which the values of observations, measurements or interpretations were obtained. The rationale is that contextualization can enable a user to figure the quality and relevance of the result, especially for reuse for another purpose.

The ISO 19156 standard, also known as Observation & Measurement (O&M) was designed for that specific need. MINnD GT1-5 described its reuse in (Beaufils, M. et al., 2019). In practice, this means the results are not provided "all alone" but associated to some additional information:

- The unit of measurement,
- The date and location of the O&M,
- The observed property,
- The method or procedure that lead to the result,
- The link(s) to related observation(s).

The latest is particularly interesting to explain the provenance of the O&M.

3.2 Provenance

Working collaboratively around BIM models must allow the pooling and capitalization of data set. The models must be able to evolve over time, throughout the life cycle of the infrastructure, and the model data (geological, geotechnical, etc.) must be reused in new projects, different from the initial project for which studies were conducted. For example, it is easy to imagine that geotechnical survey data used to size a building foundation can be reused in a new project located nearby: the same raw data from a survey can potentially be used, but the interpretation made by the geotechnical engineer may differ from one project to another.

The issue of traceability and quality of data in digital models is a key element for their subsequent use. Indeed, the BIM models carry information that have their own history, each one come from field acquisition, analysis and interpretation. Consequently, the characterization of the property of a model will have gone through the specific prism of the project with its share of hazards, uncertainties, and choices.

The MINnD GT1-5 working group conducts a reflection on this subject with the objective of guaranteeing future users of geological and geotechnical models the transparency necessary for the sharing of information within reusable models. Within this framework, the WG has produced a document called "Provenance" which proposes, for each property resulting from a geological or geotechnical model, to define the key elements allowing to trace its history from the acquisition of raw data to the achievement of a characteristic value for the given property.

Thus, for each characteristic property of a model are defined: the observation support of the raw data (survey, sensor, area of interest,...), the analysis/expertise method since the raw data to the qualified data for the needs of the project (statistical analysis, calculation, photo-interpretation...), the normative references (experimental standard, Eurocode...). The knowledge of this set allows to contextualize the data set and to realize a critical analysis of the model during its realization or its re-use.

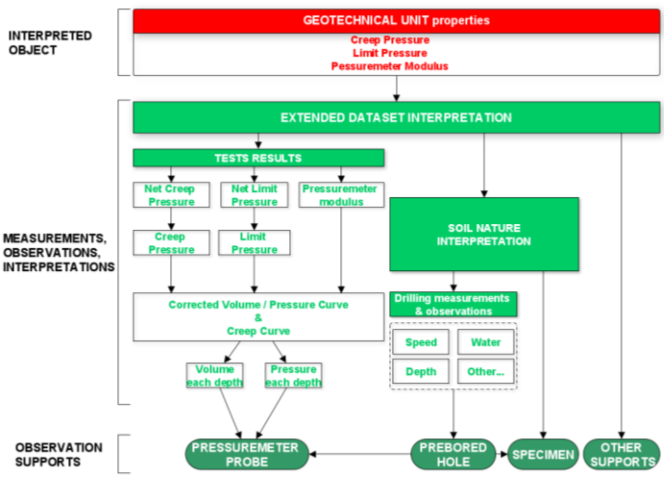

Figure 3 Importance of tracking data provenance. An example of the characterization of stress-strain relationship of the soil.

The capacity to track the provenance of the data offers several advantages:

- Figuring the interpretation process followed by the modeller,
- Assessing data quality,
- Facilitating data update, especially interpretation when new data become available.

In practice this capacity is made possible by doing links between accessible data.

4. ACCESSIBLE

The accessibility criteria is about the capacity to obtain the data and read its content. It addresses the question of the data availability (i.e. capacity to download a resource) but also what the user get and how.

4.1 Formats

The format in which the data are provided greatly influence the capacity of tools or users to understand the data and read their content. Some formats are simple to read with basic tools. They are also generally quite light, which can facilitate their sharing. Such formats include for example csv. AGS and the recent AGSi are derived from such formats, even if JSON encodings are also proposed (Chadwick, N. et al., 2019).

Some use cases may require the use of more sophisticated formats. Valuable reasons are the need of exchange of complex data, including complex geometries. STEP and IFC have been designed for that purpose and then enable to model different objects in complexed structures. Another reason might be to be able to certify the data content and then prevent from irregular edits.

All those formats here listed are yet file formats. Their use is limited to import/export. Other formats have been designed in order to facilitate exchange on the web. This includes XML format and their derivatives like GML supported by the OGC for the geospatial information. The DIGGS intiative intended to expose AGS data through this OGC protocols. Also data models from OGC like GeoSciML and GroundWaterML2 are designed to be exposed in these formats (Laxton, J. et al., 2012). The INSPIRE European Directive also recommend this encoding for the furniture of the public environmental data.

4.2 API and web services

The development of the Internet and the spread of high speed connection largely contributed to the development of Information Systems and data exchange based on the technologies of the web. In telecommunications, 3G, 4G and 5G technologies for cellular networks also contribute to facilitate data synchronization on remote devices.

Application Programming Interface or API and web services enable to expose data on the web. In OpenGIS, standards from the OGC define protocols on how those data should be accessed and delivered. The most relevant but not exhaustive include:

- OGC API Features for providing object description (eg. Geotechnical Unit, Fluid Body, …),
- OGC SensorThings API for observations and measurements (eg. tests or interpretations descriptions and results).

Such API have been successfully implemented by geoscience data providers, like national geological surveys or environmental organizations. They are also now accepted as Download Services for the conformance with the INSPIRE Directives (Kotsev et al. 2018).

Then a demonstration of the possible connection between IFC and such API has been provided during the Beijing bSI Summit. The proposed approach was to have object description and properties provided with OGC API and geometries provided in IFC.

5. FINDABLE

Data you can envisage to use are at first data you can find. In the last decades, companies like Google demonstrated the importance of indexes and search engines, or just capacity to discover existing resources in a Big Data world (Brin, S. & Page, L. 1998). The Findable deals this capability.

5.1 Identifiers, catalogs, indexes and metadata

Declaring the existence of a resource starts with recognizing it as a distinct element. This means the definition and association of a persistent and unique identifier for each resource. On the web, this is the definition of an Unique Resource Identifier (URI).

Identifiers are important for resource citation. For documents, Digital Object Identifier (DOI), that are in fact URI at first, are commonly used to enable someone to cite a paper and give access to it. Such identifiers shall be stable or persistent and not change during the data lifecycle.

Identifiers then enable to do the connections yet other components are necessary to find them. This is the purpose of indexes, catalogs and metadata.Metadata enable to get an overview of the data set. It also define parameters that will enable to find them. Once data have been associated to identifiers, solutions can be made to facilitate their discovery based on the metadata. Catalogs group and index content to make them ready for discovery.

In practice MINnD GT1-5 specified to associate identifiers to each geotechnical data: objects and their related observations, measurements and interpretations. This would enable to make the data citable and possibly findable and linked together.

The findability of the data is yet dependant of the data policy chosen by the data providers.

5.2 Geotechnical data sharing

As an example of making collective findable data, it could be cited the INSPIRE (Infrastructure for Spatial Information in the European community) directive which is an EU initiative specifically developed to establish an infrastructure for spatial information in Europe. The aiming of this directive is to make spatial or geographical information more accessible and interoperable for a wide range of purposes supporting sustainable development.

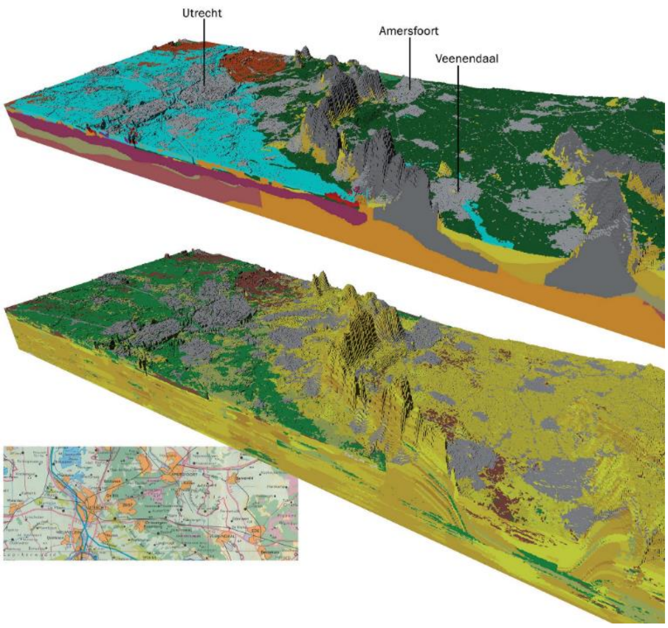

Figure 4 3D Geological model, Netherlands (GeoTop from TNO)

Another one is the possibility of sharing the geotechnical data across a wide user community: public local authorities, engineering companies, transport authorities, real estate developers, searchers, students, etc. A huge amount of geotechnical investigation data are collected in various civil engineering projects. Until now, most of the time, the data are of exclusive use for the given project often for reasons of confidentiality but as well for technical reasons: geotechnical factual data have not been collected and stored in an appropriate format, they come from different stages of investigation and from different companies and are not harmonized. Unfortunately, without a common lexical and data standard for the geotechnical tests and properties, it is often difficult, expensive and time-consuming to gather data coming from different sites, projects and operators

(Bachus et al, 2020). In addition, it is also a source of transcription errors. Therefore, at the end, geotechnical investigation data are often forgotten or even definitely lost.

The new FAIR standards created in the openBIM and MINnD projects make possible the use of the same data taxonomy and vocabulary for all the geotechnical investigation companies and enable the exchange and the recycling of the data for potential future projects or studies.

The Owners, mandating the ground investigations, will definitely find benefits of the standardization of geotechnical data. Indeed, they can load them in their own database or GIS, and have the ability of re-use historical data without having re-input the data, that ultimately reduces the cost of projects (Deaton et al., 2018). To get this result, it is necessary to specify in the technical requirements of a geotechnical investigation contract that the data must be provided in a standardized data interchange format and comply with various formats (Deaton et al., 2018).

The National Geological Surveys also play a major role in the management, capitalization and sharing of the geoscientific knowledge. Therefore, the implementation of geotechnical investigation data in the existing national geoscientific databases, as well as other physical ground properties, becomes an obvious mission of these organizations.

In France, the BRGM (French geological survey) already capitalizes and shares the geological data in open access (Nehlig et al., 2020), through its website InfoTerre™. A new project aiming to collect, store and share the geotechnical data is currently in progress. Its purpose is to allow the integration of geotechnical data coming from different sources owners thanks to dedicated web applications and to provide to the users various diffusion services: visualisation, data exports, targeted queries, edition of cross-sections, and at a longer term 3D geological models. Currently, the first step of this project, consisting in creating the geotechnical registers, including the list of soil properties, observation methods, units…, is on progress and of course is in line with MINnD GT1-5 work.

Another example is the BRO, the Dutch Key Register of the subsurface. It includes explorations data (some geotechnical and geophysical data), rights of use (mining and water acts), some infrastructures (boreholes, water wells, monitoring points), geological maps and also provides cross-sections and 3D geological models (van der Meulen et al., 2013).

Other countries are following the same trend and it is likely that in the next years, the geotechnical data be implemented in the national databases of the geological surveys all around the world.

6. OUTCOMES

6.1 International standardization

The work of the MINnD GT1-5 project was made in order to extend OpenBIM standards for geotechnics. As geotechnics is based on geosciences and aims at providing knowledge of the environment to help civil engineers to build sustainably, several standards are concerned: the one related to geosciences and the one related to civil engineering. Defining a sustainable standard imply to bridge the gap between those two worlds.

Interests from bSI to extend IFC to geotechnics start with the Port & Harbors use case. Such infrastructure is in strong interaction with its environment and needed additional concepts to describe "non-built" objects such as land and water. They were respectively called IFCSolidStratum and IFCWaterStratum.

In 2019, standardization activities were launched in order to extend IFC to address tunnel modelling. In that use case, description of the surbsurface is critical. A requirement analysis report was produced by the group and concluded that the available concepts in IFC for describing geotechnics were not sufficient to fulfil the requirements (Rives et al., 2020). The report also recommended to connect or build from the existing work endorsed by the OGC, especially GeoSciML.

Those statements lead to the need for recasting IFC Geotechnics in order to target descriptions that would fulfil to geotechnical engineering practices. A subgroup dedicated to geotechnics was then created formed in the IFC Tunnel team.

The work from MINnD GT1-5 was then shared to the bSI team and is used as a basis of work for the IFC Tunnel proposal. In practice, several members intervene in both groups in order to build a sustainable proposal for IFC. Then standardization activities shall also happen on the OGC side to strengthen the required connection between OpenGIS and OpenBIM.

6.2 Shared and accessible registries

Once defined and organised, vocabularies have to be made accessible to users. Registers as defined by the INSPIRE Directive consist in code lists with their associated values. Registries are the tool to expose those registers.

In France the French Geological Survey (BRGM) is hosting such tool to share geoscience vocabularies to the community. The BRGM registry is freely accessible (https://data.geoscience.fr/ncl/) and contains registers in different domains of geoscience, including geology (lithology, chronostratigraphy, …) and hydrogeology. While this instance mainly target national vocabularies, another instance is also available on https://data.geoscience.earth/ncl/ for international vocabularies.

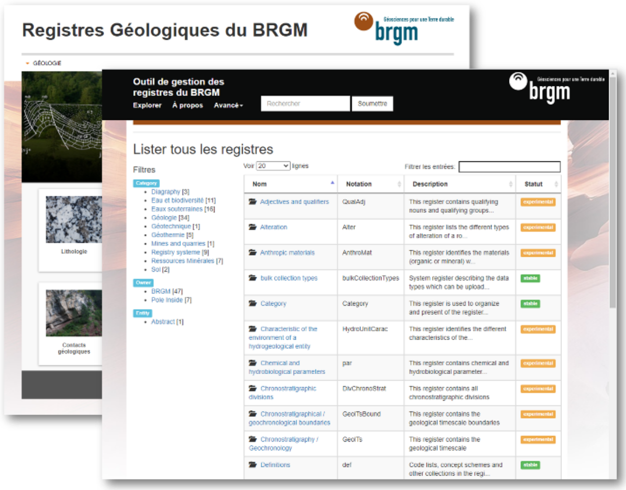

Figure 5 A snapshot of the BRGM registries and the associated tools

The vocabularies identified by MINnD GT1-5 have been proposed to feed those registries. The required Observed Properties, Procedures and Units of Measurements have then been added to the BRGM registries when they were not already available.

Such actions enable everyone to do reference to those vocabularies without ambiguity and build information systems from them.

6.3 Fostering the geoscience community

The MINnD work was mainly focused on defining standards for OpenBIM, yet it aimed at making a connection with existing knowledge and working groups. In the informatics domain, one target was to connect to existing standards for GIS oriented data (eg. the OGC or ISO). MINnD GT1-5 then contributed to strengthen the relationship between OGC and bSI to address the geotechnical data interoperability topic. One major outcome of that collaboration was the organization of the "Geotechnical Data Standardization Workshop" in January 2019.

Efforts were also made in order to create a continuity with geotechnical or tunnel engineering oriented groups. This includes the AFTES, CFGI, CFMS and CFMR which are respectively the French equivalent of ITA, IAEG, ISSMGE and ISRM.

7. CONCLUSION

The Working Group MINnD GT1-5 contributed to the definition of framework and solution for better geotechnical data exchange at the BIM era.

Following the path of OpenScience, the MINnD GT1-5 project aimed at defining geotechnical data description and management based on the FAIR principles.

The rationale is that having more qualitative geotechnical data available would help geotechnical engineers and more generally environmentalists to develop better geomodels and better manage the earth resources.

The main focus of the group was on the definition of right semantics and objects to express the richness of the data collected and interpreted. Such elements contribute to describe the data with the appropriate wordings and no ambiguity, thus its interoperability.

Efforts were also made to address the question of data quality. A solution was proposed to enable the users to express data provenance and measurement methods and finally make data reusable.

In addition to those technical aspects, the MINnD GT1-5 project also studied and discussed the necessary actions in order to introduce the proposed standards in the current practices.

The MINnD GT1-5 promotes the reuse of data models and technologies used by geological surveys and other environmental organisation. The main reasons are to defend an unity or at least interoperability in terms of data description in the geoscience community and to enable a possible cost and time saving for further projects. The rationale is then that the format to use for geotechnical investigation for a project shall not be different from the one geological surveys would provide on the web.

It is also worth noticing that the geotechnical survey companies, which are at the source of the data collection, play a major role in the standardization of the geotechnical data. Of course, after a period of appropriation of the data structuration, they will obviously find an internal benefit for a better capitalization of their data, traceability of the analysis and interpretation, and time saving for the data exchange with their clients or partners. In addition, the use of standardized format of geotechnical factual or interpreted data enables data exchange independently of the softwares that can be used in a project.

8. ACKNOWLEDGEMENT

The work of MINnD GT1-5 is born from the collaboration of several members from multiple French organizations (public, research, engineering, owners) including ANDRA, BRGM, CAN, COLAS, CETU, EDF, EGIS, Géolithe, GEOS and SETEC.

9. REFERENCES

Bachus, R., Machairas, N., Cadden, A. (2020): Standardizing Geodata Transfer and Storage, Deep Foundations, May-June 2020.

Beaufils, M., Le Hello, B., Lorentz, J., Castro-Moreno, J., Beaudouin M., Grellet, S. (2019). Geotechnical data standardization and management to support BIM for Underground Infrastructures and Tunnels. In: World Tunnel Congress 2019, Napoli, 3–9 May 2019. https://hal-brgm.archives-ouvertes.fr/hal-02056440

Beaufils M., Le Hello B., Lorentz J., Castro-Moreno J., Beaudouin M., Grellet S. (2020) Proposition of Sustainable and Long-Term Geotechnical Data Management to Support Building Information Modeling. In: Correia A., Tinoco J., Cortez P., Lamas L. (eds) Information Technology in Geo-Engineering. ICITG 2019. Springer Series in Geomechanics and Geoengineering. Springer, Cham. https://doi.org/10.1007/978-3-030-32029-4_44

Brin, S. and Page, L. (1998). The Anatomy of a Large-Scale Hypertextual Web Search Engine. In: Seventh International World-Wide Web Conference (WWW 1998), April 14-18, 1998, Brisbane, Australia. http://ilpubs.stanford.edu:8090/361/. Retrieved August 10, 2021.

Chadwick, N., Farmer, D., Chamfray, J. & Miles, S. (2019). Extension of the AGS Format to Incorporate Ground Model and Interpreted Data. 10.1007/978-3-030-32029-4_20.

Deaton, S. (2018): What are the benefits of geotechnical Data Interchange, 69th Highway Geology Symposium, Sept. 2018.

Kotsev, A., Schleidt, K., Liang, S., Van Der Schaaf, H., Khalafbeigi, T., Grellet, S., Lutz, M., Jirka, S. and Beaufils, M. (2018). Extending INSPIRE to the Internet of Things through SensorThings API, GEOSCIENCES (SWITZERLAND), 2018, ISSN 2076-3263, 8 (6), p. 221, JRC112221. https://www.mdpi.com/2076-3263/8/6/221

Laxton, J., Serrano, JJ. & Tellez-Arenas, A. (2010) Geological applications using geospatial standards – an example from OneGeology-Europe and GeoSciML, International Journal of Digital Earth, 3:sup1, 31-49, DOI: 10.1080/17538941003636909

Nehlig, P., Loiselet, C., Thièblement, D. (2020): Où en est la connaissance du sous-sol national ?, BRGM Geosciences n°24, June 2020.

Pérez-Díaz, L., Alcalde, J., and Bond, C. E. (2020) Introduction: Handling uncertainty in the geosciences: identification, mitigation and communication, Solid Earth, 11, 889–897, https://doi.org/10.5194/se-11-889-2020.

Rives, M., Borrmann, A. (2020) IFC-Tunnel Project. Report WP2: Requirements analysis report (RAR). Status: v1.0 – 2020-07-31. https://app.box.com/s/3p28520cgser0sa1bvunhc99bt4qhuza/file/711362091723. Retrieved August 16, 2021.

Van der Meulen, M., Doornenbal, J., Gunnink, J., Stafleu, J., Schokker, J., Vernes, R., . . . Van Daalen, T. (2013). 3D geology in a 2D country: Perspectives for geological surveying in the Netherlands. Netherlands Journal of Geosciences - Geologie En Mijnbouw, 92(4), 217-241. doi:10.1017/S0016774600000184.