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**GEOTECHNICAL BIM FOR QUANTITY TAKE-OFF IN TUNNELING
STRUCTURES WITH GROUND DEFORMATION**

**IZMERE GRADBENIH KOLIČIN PREDORSKIH KONSTRUKCIJ NA
OSNOVI GEOTEHNIČNEGA BIM MODELA**



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Building Information Modelling

Master thesis No.:

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Izvleček:

Implementacija informacijskega modeliranja zgradb (BIM) na področju infrastrukturnih projektov izpostavlja več vprašanj z različnih vidikov. Eno izmed njih postopek izmere in določanja količin pri predorskih konstrukcijah, kjer se za tehnologijo gradnje zelo pogosto uporablja nova avstrijska metoda (NATM). Pri oceni količin za izkop in primarno oporo v predorih je treba upoštevati deformacijo tal, kar pomeni, da bi morali biti geotehnični postopki integrirani v BIM. Avtor z bibliografskimi pregledom prikazuje trenutno stanje in razvoj standardov BIM za infrastrukturo s poudarkom na predorskih konstrukcije. Predstavljena so orodja za BIM geološko in geotehnično modeliranje ter njihova interoperabilnost z projektantskimi orodji. Na primeru BIM modela projekta Drugi tir Divača - Koper (2TDK) kot študije primera avtor predstavi delovni postopek za določanje količin NATM tehnologiji gradnje ob upoštevanju deformacije tal, ki vključuje geotehnično analizo kot del BIM procesa. Kot rešitev za izmenjavo informacij v fazi gradnje predlaga uporabo geološkega modela izkopa.

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Abstract:

The implementation of Building Information Modelling (BIM) methodology in the infrastructure field, awakes several questions in different aspects. One of them is about the workflow for the quantity take-off in tunnelling structures where the New Austrian Tunneling Method (NATM) is used very often for the excavation process. The estimation of quantities for the excavation and primary support in tunnels requires to consider the ground deformation, meaning that geotechnical processes should be integrated with BIM processes. The author explores the current development of BIM standards for infrastructure and tunnelling structures through bibliographical research and will explore geotechnical tools for BIM in tunnelling structures, geological and geotechnical modelling, and the interoperability capabilities between modelling tools and geotechnical tools. Using the Second Track Tunnel Divača – Koper (2TDK) project as a case study, the author proposes a workflow for the quantity take-off in NATM Tunnels considering the ground deformation integrating the geotechnical analysis as a part of the BIM process. It proposes a geological excavation model as a solution for information management during the excavation and construction phases.

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1 INTRODUCTION

The decision to use a BIM methodology in the design process is justified by significant technical and economic factors. The main objective is early optimisation and risk minimisation, in terms of cost and time by having a direct overview of the excavation geometry and volume and by including all technical aspects and disciplines in the design from the very beginning. Both the geotechnical design of the rock excavation and rock support and the subsequent tunnel inner works such as drainage, safety installations, signalisation and energy are implemented in the model and at the same time contribute to the overall project planning. Numerous surface and underground structures, including subway and railway tunnels in operation and near the new line, result in a complex geometric layout, whereby the geotechnical influences and interactions on each of these structures are to be minimised. The aim is to actively counteract the loss of information during the entire life cycle of the project by creating a 3D model and relevant metadata as a single source of information during design and for further use during operation and maintenance. Facilitate communication and create a better understanding of communication between technical, political and public channels [1].

Nowadays, BIM is starting to be implemented in infrastructure projects, where the scale and the amount of data to manage is significant, which means an increasing developing of digital tools for infrastructure, BIM-enable, for modelling and information management for all the project phases.

» Tunnelling is an exciting and rapidly evolving technology. Pioneering processes are commonplace and innovative thinking continues to rewrite the rules. In tunnelling is an exciting and rapidly evolving technology. Pioneering processes are commonplace and innovative thinking continues to rewrite the rules. In civil engineering, tunnelling is one of the few areas where new horizons are commonplace and innovative thinking continues to rewrite the rules. In civil engineering, tunnelling is one of the few areas where new horizons are constantly being discovered« [2].

Tunnelling structures are one of the most complex projects in infrastructure and require a strong relationship with the geological and geotechnical modelling, analysis and information management. This document will explore current advances for geotechnical BIM, specifically for geological and geotechnical modelling and test interoperability cases for BIM to Finite Element Analysis, to estimate the ground deformation in tunnels to be excavated following the New Austrian Tunnelling Method (NATM). Furthermore, it will study the workflow and general recommendations for the quantity take-off in tunnelling structures, considering the ground deformation as a primary modifier to estimate excavation and shotcrete volumes and the importance of the definitions in the BIM Execution Plan (BEP), using the case of study the Second Track Tunnel Divača – Koper (2TDK).

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2 BACKGROUND AND RELATED WORK

2.1 Tunnelling Structures

A tunnel is an underground passage, used as a solution in civil engineering for railways, roadways, aqueducts and many other applications. Nowadays, it is becoming a usual solution in transportation to sorting the difficulties of the topography across the alignment of the road and allows to design faster and curveless routes.

There are different types of tunnels depending on the construction method, as is shown in Figure 2-1. Mainly, two kinds of tunnels can be distinguished from the material to across, water or land. For underwater tunnels, they could be immersed or bored. For those under the ground, can be classified as mined/bored or cut and cover.

For the mine or bored tunnels, the most common excavation method is the Sequential Excavation Method – SEM. This last is the primary excavation method referenced in this document.

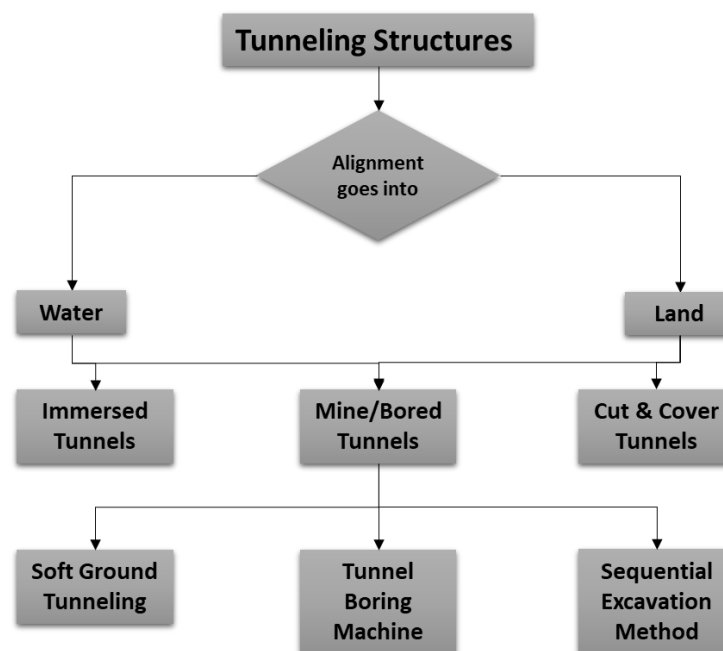


Figure 2-1. Tunnelling Structures Types. Source: Modified from [3]

2.1.1 Sequential Excavation Method: The New Austrian Tunneling Method (NATM)

A prevalent sequential excavation method is the New Austrian Tunneling Method, developed by the Austrian tunnelling specialist von Rabcewicz, Pacher and Müller-Salzburg in the years 1957 to 1965. The central concept of the method consists of a conventional heading followed by the installation of support, usually shotcrete and rock bolts, following the principles of the observational method. During

the excavation, ground deformation requires to be minimum but at the same time should be sufficient to mobilise the ground strength [2].

The New Austrian Tunneling Method (NATM), also commonly known as the Sequential Excavation Method (SEM), uses the inherent strength of the rock mass to support the ceiling during excavation. As this self-supporting capability provides economy, flexibility in uncovered ground conditions and considerable design variability, NATM is widely used for underground structures. NATM tunnels depend mainly on the circular length, the type of support and ground conditions such as shear strength, deformation and groundwater level. Excavation methods and supporting patterns are predefined as “types” in the design phase [4].

The excavation process is made by stages, dividing the cross-section of the tunnel in two parts, the top heading and the bench. Then, each part is split along the tunnel length into excavation steps. These excavation steps are defined depending on the ground geological and geotechnical behaviour along the alignment, as is schematised in Figure 2-2. The definition of an excavation step is due to the total unsupported length is possible to excavate at once, maintaining stable conditions during the support installation. This procedure concept is important to create a BIM model for quantity take-off purpose because it defines the main division units of the model and is required for a 4D and 5D simulation.

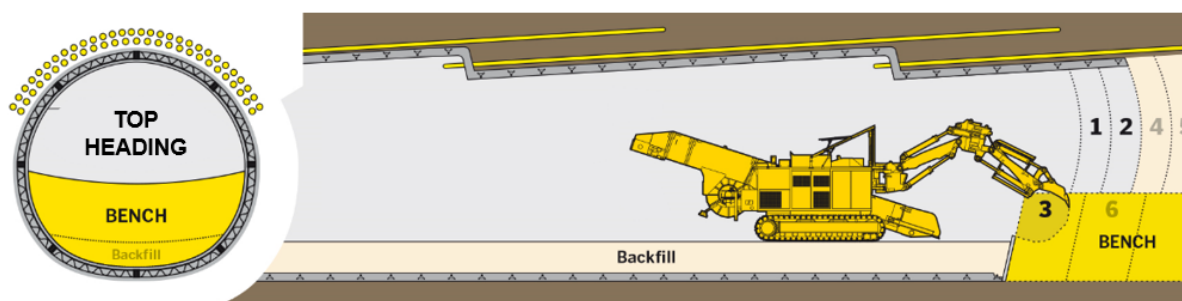


Figure 2-2. New Austrian Tunneling Method [5].

2.2 Ground deformation in Tunneling Structures

As it was mentioned before, during the excavation, a deformation or ground deformation is expected because the ground stresses release. The geotechnical analysis for the tunnelling design has as principal scope define the necessary support along the tunnel alignment, the expected geotechnical threats and the estimated ground deformation. The resultant deformation modifies the design section required for the tunnel. In order to grant the correct dimensions in the inner liner is essential to consider the ground deformation during the excavation, meaning that the theoretical excavation line must have the ground deformation involve, as is shown in Figure 2-3.

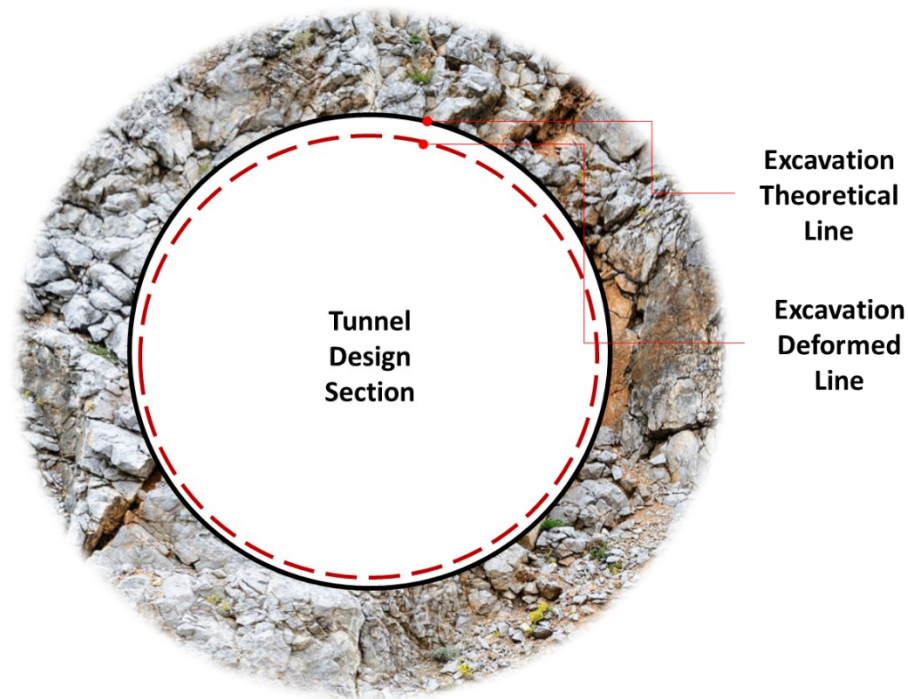


Figure 2-3. Excavation theoretical line

For the geotechnical analysis, some typical or critical zones are selected depending on the geologic conditions. The designing process starts analysing the typical/critical zones of the tunnel and defining the support required to minimise the ground deformation. As a result of the designing process, typical supporting types are defined and assigned along the alignment. In consequence, the tunnel has another division unit, the support type, that is directly related to the excavation step, which is a result of the designing process also. In summary, the excavation is divided into three different criteria, as is shown in Figure 2-4.

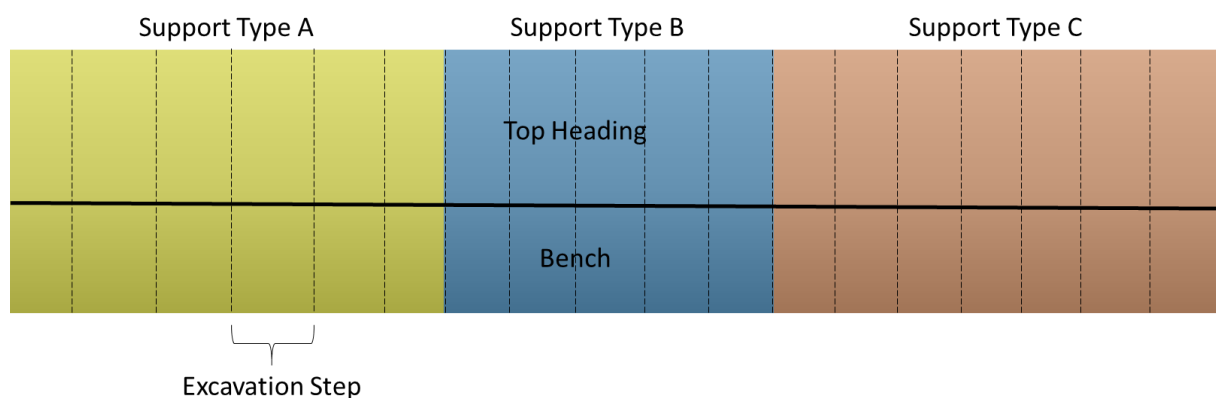


Figure 2-4. Tunnel excavation division criteria.

2.3 Geotechnical Information Modelling

Building Information Modeling (BIM) is being used for several purposes in the AEC industry, because all the benefits that came with the digital tools such as better representations of building elements, better coordination between multidisciplinary designers, better quantity and cost estimation, among others [6]. These advantages are more notorious in a large-scale project as tunnelling structures, where the volume of information is vast, the coordination is a hard task, and the precision in the quantity estimation needs to be high.

The Federal Highway Administration (FHWA), along with the American Association of State Highway and Transportation Officials (AASHTO), American Road and Transportation Builders Association (ARTBA) and the Associated General Contractors of America (AGC) created the concept of Civil Integrated Management (CIM), defined as the technology-enabled collection and use of accurate data through the transportation asset life cycle, including planning, environmental assessment, surveying, design, construction, maintenance, asset management and risk assessment [7]. So it is possible to claim that CIM could be used as a BIM counterpart for infrastructure projects.

With the increasing implementation of BIM on tunnelling structures, the geology becomes a new challenge. The ground conditions are a crucial input for the designing process; in response, software developers made significant progress in digital tools for geology modelling, considering the interoperability with BIM software.

Based on the BIM or CIM definition, a proposal for geotechnical BIM is the concept Geotechnical Information Modelling (GIM), referring to the set of digital tools, processes and standards for the collaborative management of surface and underground data, during the asset life-cycle, adapting the definition of Geological Information Modelling provided by Persson in 1997 [8].

BIM or CIM, present the term »accuracy« in their definition. Still, geology representations are not exactly the best example for accuracy due to the fact they are made by an interpretative method, using sample points (boreholes, structural data measures and geophysical exploration methods), observation, interpolations and geometric projections. As a result, an excellent geological model is precise but not necessarily accurate. Even though this condition is intrinsic to the geology modelling process, digital tools are a solution to increase precision and accuracy and allow to integrate such an essential part of the project in the GIM processes.

It is necessary to mention that there is a fundamental difference between BIM and GIM, about the accuracy, due to the natural condition of the ground. In buildings, it is possible to reach high levels of precision and accuracy because digital objects represent real human-made objects, where geometry, properties and positions are possible to control. Instead, digital geology representations are based in a pre-existent condition that human can not control, and are based on an interpretation of single random

points on the surface and sub-surface exploration. »This normally includes interpolation or extrapolation of the determined ground information. This can lead to a false impression of exactness in the digital (3D) display. The ground model locally deviates from reality as depicted before« [9].

From a geological model is created a geotechnical model, which beyond the geometry (strata) it contains the information regarding the mechanical and deformation behaviour of each stratum and is made for different purposes, mainly for finite element analysis, limit equilibrium methods, earthworks design, foundations, mining designs, time and cost estimation, among others. »The geological 3D model permits the designers and engineers to simply produce any geological profile sections in vertical, horizontal or inclined orientation from the geological prediction« [10].

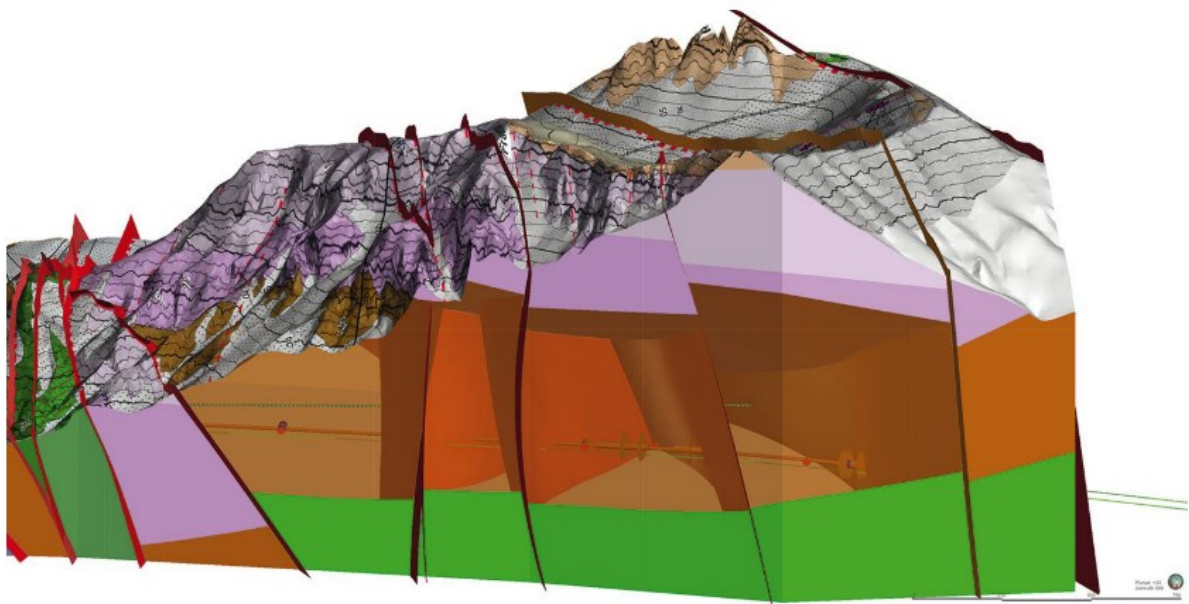


Figure 2-5. 3D geological model [10].

In the case of tunnelling structures, geological and geotechnical information is required during the planning, designing and construction phases of the project. That is the reason why the geological and geotechnical models must be included in the BIM process of this kind of civil projects.

2.4 BIM for Tunneling Structures

In large-scale tunnelling projects, a large amount of data is usually collected and exchanged during both the design and construction phases. This data comes from a variety of sources and can be roughly divided into site data, design data, machine data, monitoring data and simulation data. Taking into account the different effects of the various sub-models and the related project data on the overall tunnel design and construction process, a geotechnical terrain model, a tunnel lining model and a model of the built environment are created individually and then exchanged within an open IFC environment using the IFC concepts proxies, property sets and Model View Definitions [11].

Tunnelling projects can be dealt with two different approaches depending on a primal differentiation or division in the complete project. Tunnels require annexed buildings, mainly in the portal areas (Figure 2-6) where some services are needed. According to that, the BIM model has to be addressed by two separate workflows to produce one single result. First, punctual or single buildings, which BIM model could be done mostly with predefined or open object libraries and all elements currently have a proper IFC element type defined. Second, the civil works, as tunnels, railroads, roads, earthworks, among others. This kind of elements requires to adapt or create objects which the IFC element type still in progress to be developed. For these matters, it is essential to determine the best solution in modeller software, because every software is developed for a particular solution. For instance, Revit or Archicad are excellent solutions to perform building's BIM models but does not have the proper tools to represent civil infrastructure, in which case a better solution may be Autocad Civil 3D or Infraworks.

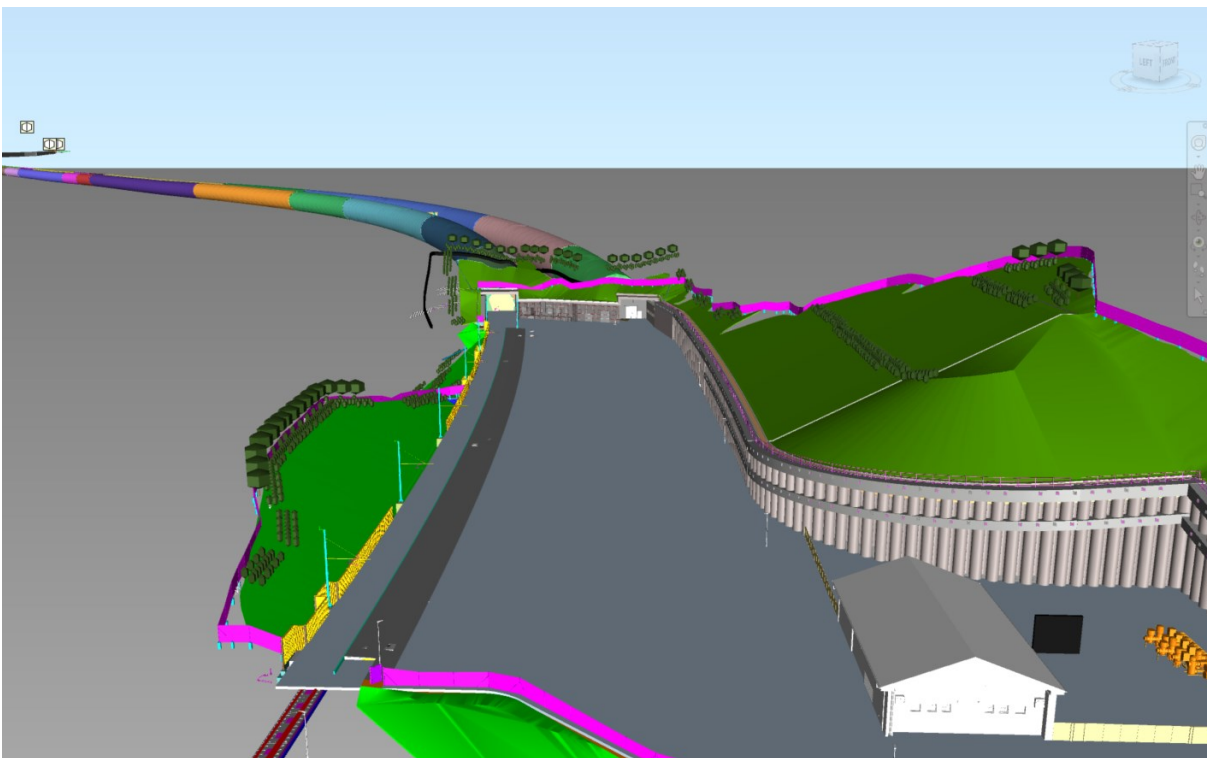


Figure 2-6. 2TDK BIM Model [12].

In the construction phase of a project, the planned workflows are implemented. In order to identify problems early on and to document them consistently, these processes should be monitored continuously. Therefore, information systems are used during the construction phase of a tunnel project. In addition to monitoring the construction progress, documentation of the production of the structure with delivery notes and acceptance protocols is an integral part of the BIM process [13].

Large-scale projects require to be modelled in several single models by different multidisciplinary teams. A task that produces a significant amount of information and needs big effort in coordination and

collaboration. Besides, the nature of underground and tunnel construction differs significantly in the degree of scientific data interpretation, which extends over the time and scope of the projects. Successful implementation requires the use, exchange and translation of data in various formats to be used as input, parameters, factors and constraints. A fairly common issue for engineers is dealing with data in a form difficult to be handled, such as reports, measurements and observation results.

Tunnels also have the unique feature of influencing and interacting with both underground conditions and the environment. This interaction is dynamic, especially during the construction phase, and consists of the critical concept that requires constant work on each part of the project life cycle. In this way, additional parameters and difficulties arise, which lead us to move on to non-conventional methods and procedures. One of the most important breakthroughs that BIM has brought in engineering is the complete assimilation of the structure's calculations with semantics, geometry, sequence and all other aspects of the project. Analyses and calculations are no longer treated as isolated tasks, but they continuously interact with all parts and produce a realistic representation of structural performance. The geometric model is used directly by the respective computational calculation software to perform the analysis [14].

Using BIM in tunnelling structures, specially NATM tunnels, as soon as the excavation work and the supporting installation begins, the engineers are able to follow up from the already performed simulation of the real construction phases. All federated models, documents and calculations are updated continuously in all processes to ensure consistent data and to achieve transparent, accurate and reliable workflows. As a result, the construction site reacts more quickly to design changes, the adoption of solutions is more practical, faster and more efficient, and project execution is improved.

With the unique characteristics of the tunnelling projects, some BIM uses that are required during the design, construction and maintenance phases of the project are the data management, documentation, 2D and 3D representation, quantity take-off, 4D and 5D simulation. Regarding the 3D representation, there is still a challenge to improve, the parametric design for the tunnel elements using the available modelling tools.

Most people used to the »traditional« modelling software for buildings could think is also the best option to model tunnels or any infrastructure, using parametric design but, currently, there are many and better alternatives. The challenge is to keep learning and trying tools that can reach optimal solutions.

2.5 IFC Schema for Infrastructure

The Industry Foundation Classes standard (IFC) published by the International Alliance for Interoperability (IAI) plays a very important role in the process, as it is a standard for data sharing throughout the project life cycle, globally, across disciplines and for technical applications in the AEC industry [15].

IFC provides information about the common objects shared by many applications throughout the construction project life cycle and enables interoperability of construction information through the software used in the AEC industry. The IFC data schema is an object-oriented model that contains semantic information and property information of the components in addition to the shape information of structures; it represents the objects, properties and relationships using entities [16].

The IFC data schema is a vital definition to standardise how software read and classify the different elements in a model and the information within. This IFC schema has been developed by BuildingSMART. For the latest version (4.1.0.0), they introduce the element type *IfcCivilElementType* to define an element specification of civil engineering works, as a general classification, but for a specific type definition is required to add an *IfcLabel* to define the exact element type.

The entity *IfcCivilElement* was added in the IFC schema as a generalisation of all elements within a civil engineering works. The inheritance schemas of these entities are shown in Figure 2-7. Within the *IfcCivilElement*, some property sets entities were defined for more typical infrastructure projects such as roads and bridges as is presented in **Annex A**.

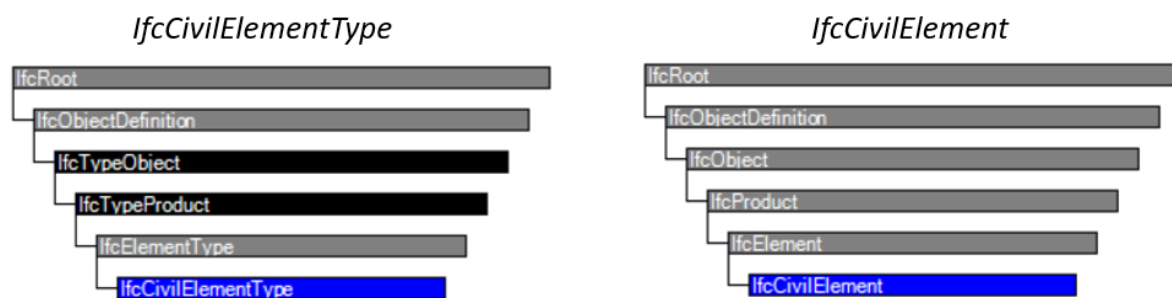


Figure 2-7. IfcCivilElementmType and IfcCivilElement inheritance schema.

However, for tunnelling structures, there is no specification yet from BuildingSMART. *IfcElement* includes all physically existing objects, such as various structures that represent shapes by occupying space as the generalised elements of each component that make up a product in the construction industry. The *IfcCivilElement* in the existing IFC data schema only contains subtypes for generic civil structures, therefore an *IfcTunnelElement* entity is required to represent design information of tunnel structures.

Lee, Park and Park [16] proposed in 2016 an IFC data schema for NATM tunnels by the addition of entities for the spatial/physical representation of the tunnel, along with their corresponding characteristic sets, and the relationships between them. The additional IFC spatial elements for NATM tunnels are shown in Figure 2-8, and an example of the implementation of physical elements is shown in Figure 2-9.

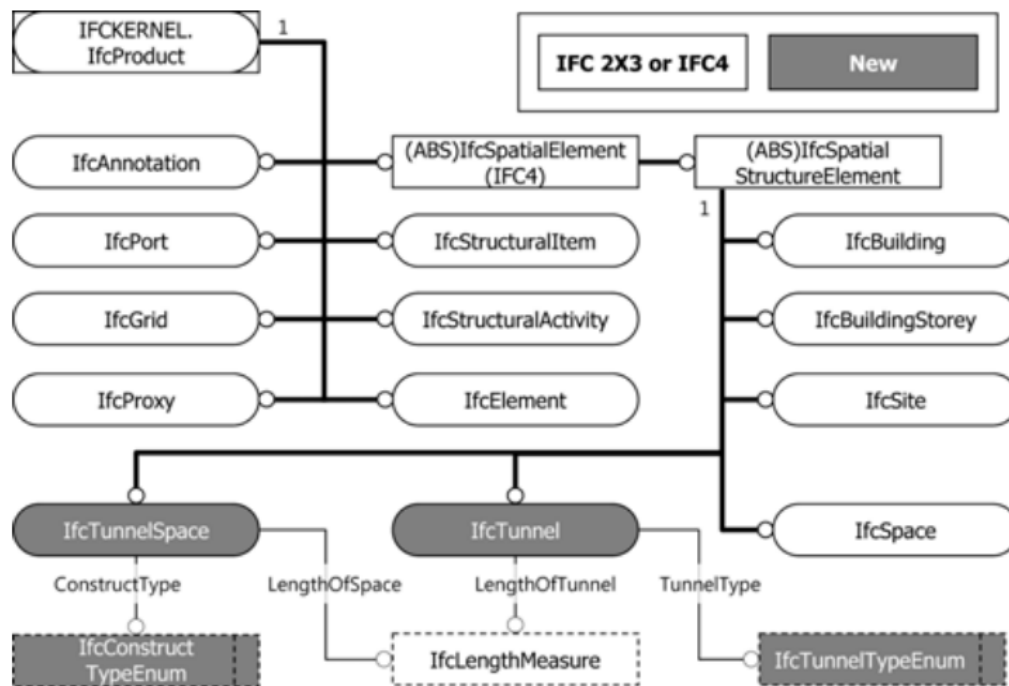


Figure 2-8. Additional IFC Spatial Elements for NATM Tunnels [16].

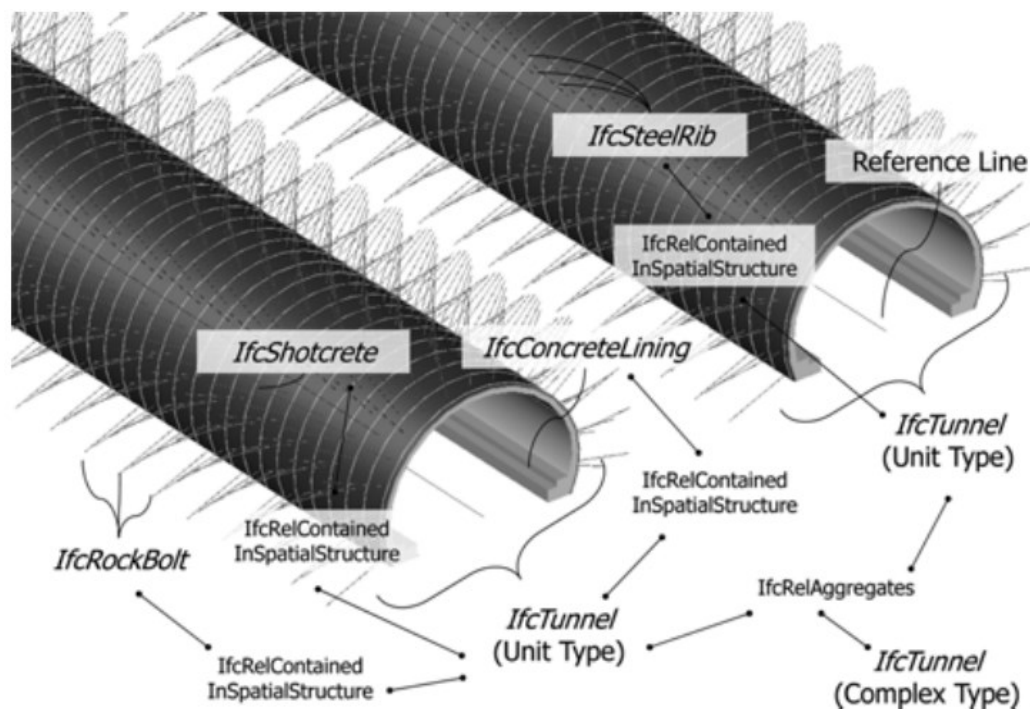


Figure 2-9. Implementation of IFCTunnel Example [16].

2.6 Level of Development for Infrastructure and Level of Geometry for Tunneling

The Level of Development is an essential concept for any BIM project. It refers to the degree of readiness of the model to fulfil the requirements for several BIM uses of the model, during the project life-cycle.

However, there is not a standardised LOD for infrastructure. The latest version (2019) of the »Level of Development (LOD) Specification« made by BIM FORUM include some elements for infrastructure in the group »civil«, but still far from being as complete as is for buildings. Some designers chose to use the LOD fundamental definitions introduced by BIM FORUM [17] are:

LOD 100: Elements are graphically represented as symbols or any generic geometry, showing the existence of a component, but not its shape, size or precise location. The information must be considered approximate.

LOD 200: Elements are graphically represented as a generic object with approximate quantities, size, shape, location and orientation. They may be recognisable as the object they represent or volumes for space reservation. Non-graphic information may be attached to the model element.

LOD 300: Elements are graphically represented as the specific object in terms of quantity, size, shape, location and orientation. It means, the element can be measured directly from the model object without referring to non-graphical information. The project origin is defined, and the element is located accurately respect to the project origin. Non-graphic information may be attached to the model element.

LOD 350: Elements are graphically represented as the specific object in terms of quantity, size, shape, location and orientation, including parts required for coordination with nearby elements. The project origin is defined, and the element is located accurately with respect to the project origin. Non-graphic information may be attached to the model element.

LOD 400: Elements are graphically represented as the specific object in terms of quantity, size, shape, location and orientation with detailing, fabrication, assembly, and installation information. The project origin is defined, and the element is located accurately with respect to the project origin. Non-graphic information may be attached to the model element.

With the increasing usage of BIM for tunnelling projects became the necessity of defining a LOD and a further standardisation about this. The German Committee for Underground Construction (Deutscher Ausschuss für Unterirdisches Bauen – DAUB) propose in 2019 [9] the following definition of Level of Geometry (LOG) for tunnelling structures:

LOG 100: Conceptual representation of the tunnel tube as a structure in the form of an idealised shell. The outer edge of the structure describes the theoretical excavation line.

LOG 200: Excavation, outer shell and the inner shell as separate model elements (according to the planning state). Spatial representation of the securing means by encasing. Separate representation of the expansion areas. Modelling of the interior, including shoulder and filling concrete as a separate encasing element.

LOG 300: Representation with exact dimensions, materials and position. Excavated body and outer shell separated by partial cross-sections, plus other additionally required components such as niches, shafts or pumping stations. Inner shell separated by the vault, invert shoulder, filling concrete and false ceiling. Representations of the interior fittings separated from shoulder and filling concrete utilising an encasing.

LOG 400: Detailed and accurate representation required for the execution phase. Excavation and outer shell divided into partial cross-sections and advance lengths. Modelling of the sealing system divided into individual components. Assignment of the joint types to the respective model elements according to the method of installation.

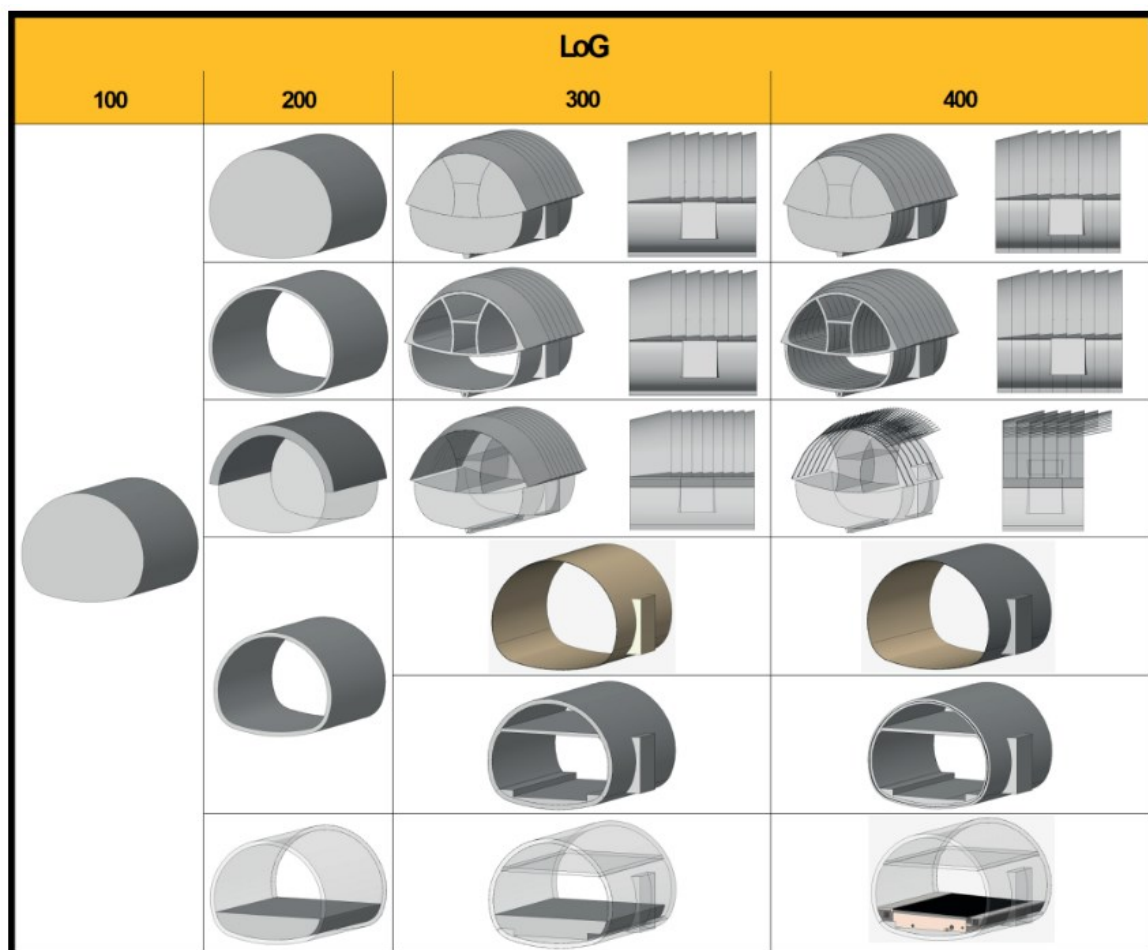


Figure 2-10. Overview of Levels of Geometry (LOG) in conventional tunnelling [9].

A new discussion would be about the applicability of these definitions of LOG in the case of the excavation and shotcrete model objects because of their particular condition they represent. The excavation model is made based on the theoretical excavation line that is the result of adding to the design cross-section the thickness of the inner concrete, the waterproof isolation, a constructive tolerance and the ground deformation, as is shown in Figure 2-11.

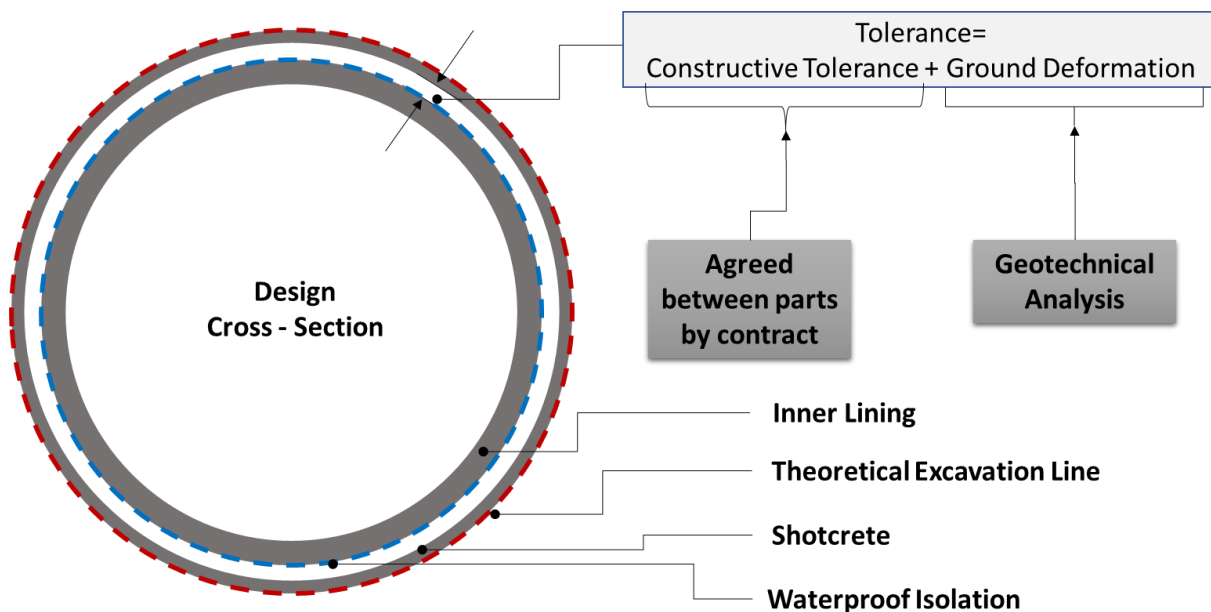


Figure 2-11. Theoretical Excavation Line

Therefore, the object model is representing the excavation before the deformation happens because it is the correct approach for the quantity take-off, and it is possible to assign a LOG 300 to this condition. However, complications begin with the shotcrete, which has a variation in the geometry with time, because of the ground deformation. In this case, the shotcrete is represented before the deformation to estimate the proper quantities, meaning an exact geometry, meaning a LOG 300. Still, the result is a void space between the shotcrete and the inner concrete, that would never exist. In consequence, the exact geometry of the tunnel is not represented, and the resultant LOG of the compose model would be LOG 200.

3 GEOTECHNICAL BIM

Considering the dynamism on the geometry in tunnelling structures due to the geological and geotechnical context and the deformation or ground deformation during the excavation process is critical to involve the analytical analysis in the BIM process. It means, the BIM process must include since the early design stages, the geology, the geotechnical data, analysis and design. Merge these processes become with several challenges, as the integration of the geotechnical data management, the interoperability with geographic information systems (GIS) and the approach of BIM to Finite Element Analysis (FEA).

Nowadays, there are several solutions for the geotechnical data management, as Openground Cloud from Bentley to collect in a single database all the borehole information, field tests, laboratory tests, analysis and all kind of geotechnical data during the project life-cycle (Figure 3-1). These tools are already integrated with BIM software through API's, as the Geotechnical Module for Autocad Civil 3D, that is a plug-in based on the Keynetix applications HoleBASE and KeyHOLE.

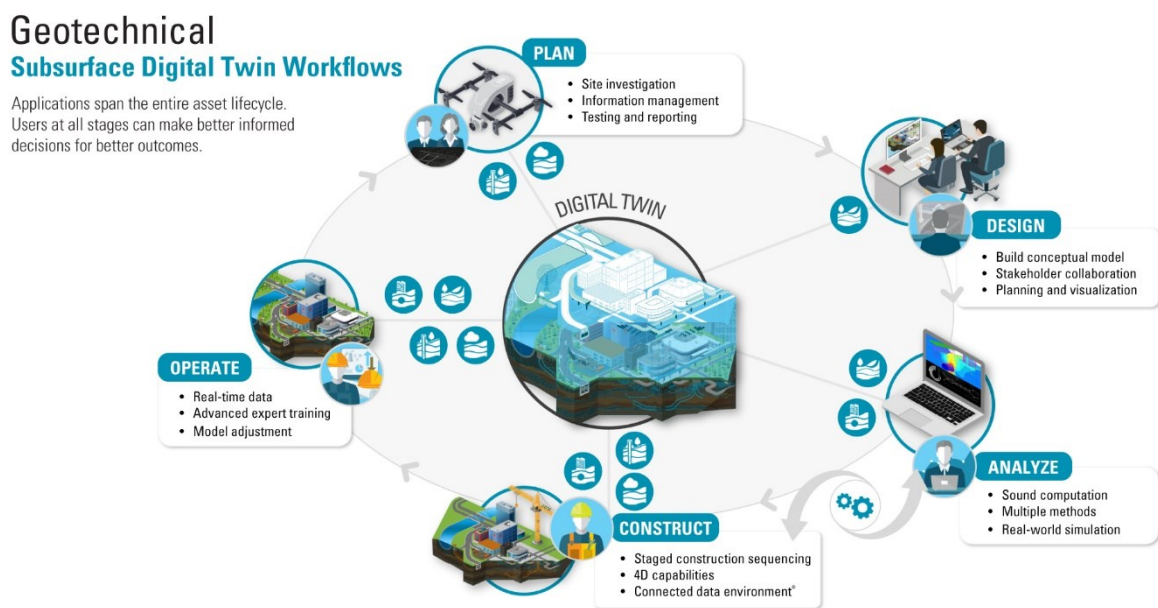


Figure 3-1. Geotechnical Workflows Ground to Cloud [18].

Furthermore, the interoperability development for geotechnical finite element analysis is an early stage. There are some cases as Plaxis 3D and Rocscience RS3 where 3D geological models can be imported and exported to a BIM environment. In tunnelling projects, the designing process starts with the geological model, then the geometric design (alignment and cross-sections), the geotechnical analysis where the supporting types are defined with a calculated ground deformation.

3.1 Geological Modelling

The first step in the geotechnical process is creating a geological model. Traditionally, geologists made 2D representations (Figure 3-2) based on the boreholes, geophysical tests, surface data and rock mass structural measures. Essentially a geological 2D representation is a plane containing geo-spatialised information, based on basic linear interpolation.

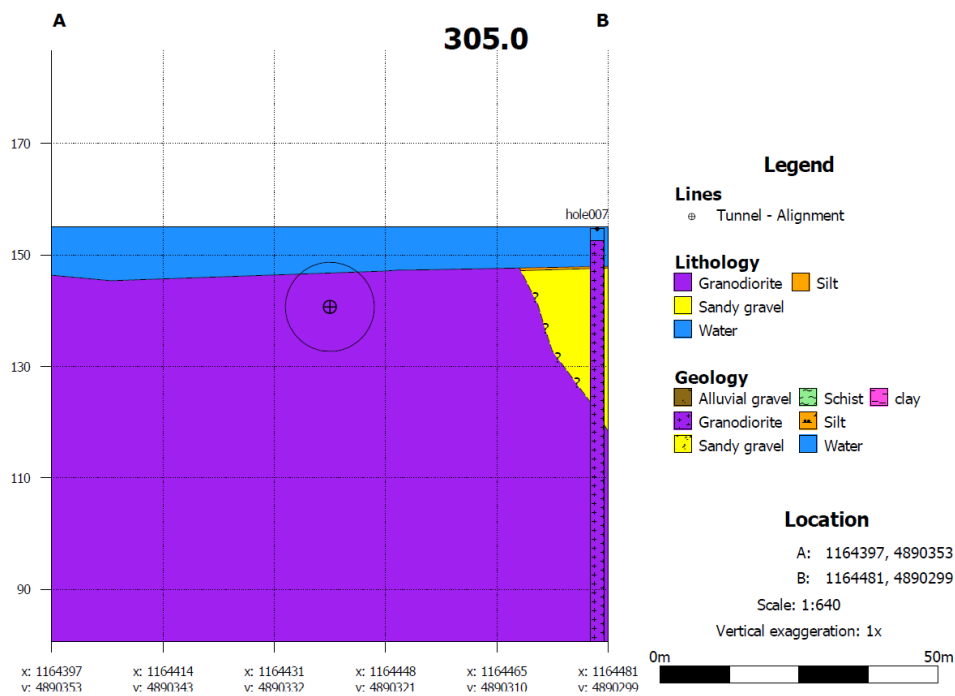


Figure 3-2. Geological 2D Representation.

Often, a linear interpolation is good enough for a 2D representation for most of the geotechnical analysis. Whoever, this interpolation is done in just one axis. For example, in an XY plane, the interpolation between boreholes is made in the X-axis, relocating the borehole virtually into the analysis section in the Y-axis, without any interpolation, just keeping the original elevation (Z) of the borehole, as is represented in Figure 3-3.

This method is commonly used to produce simple geological/geotechnical 2D representations and can be considered precise in regular soils stratigraphies, where is expected to not have larger variations in the soils layers. The case is different in more complex situations, as it is in rock masses where the linear interpolation is complemented by geometric projections because of the discontinuities in it (Figure 3-4). Rock masses have several conditions that influence the geological representations, as the failures, joints and stratigraphy. These characteristics variate in a 3D space, making it difficult to have precise 2D representations on this complex geological context. Commonly, tunnelling projects need to deal with this complex behaviour of the geology, along the alignment.

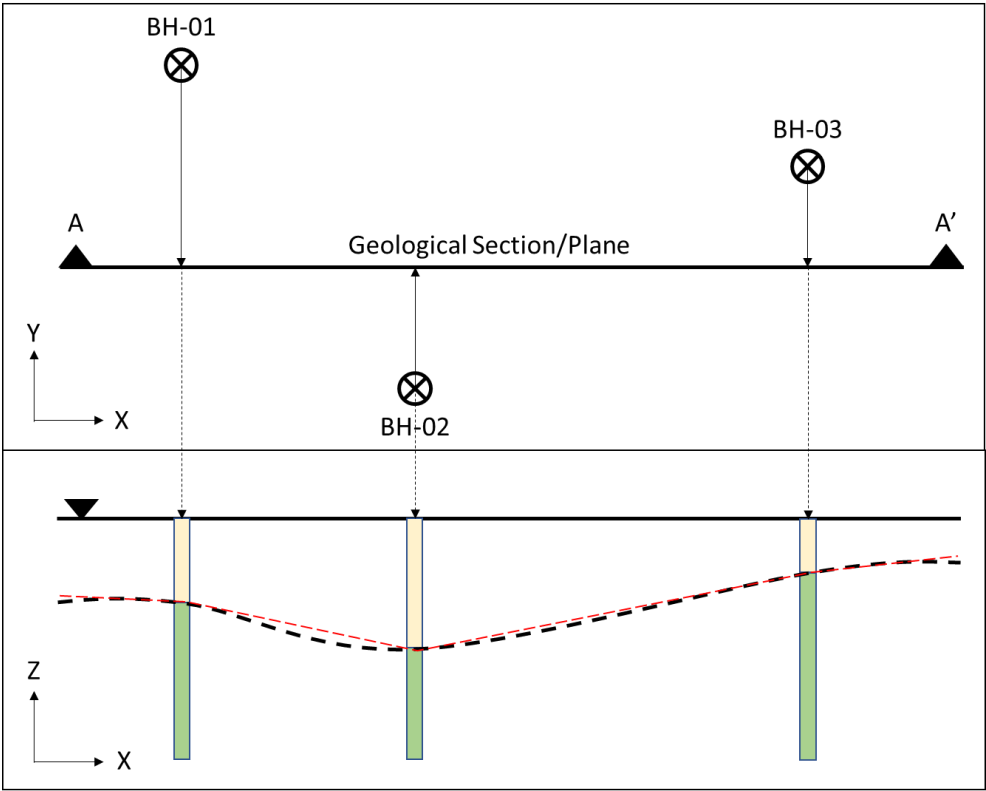


Figure 3-3. Lineal interpolation for a 2D geological representation.

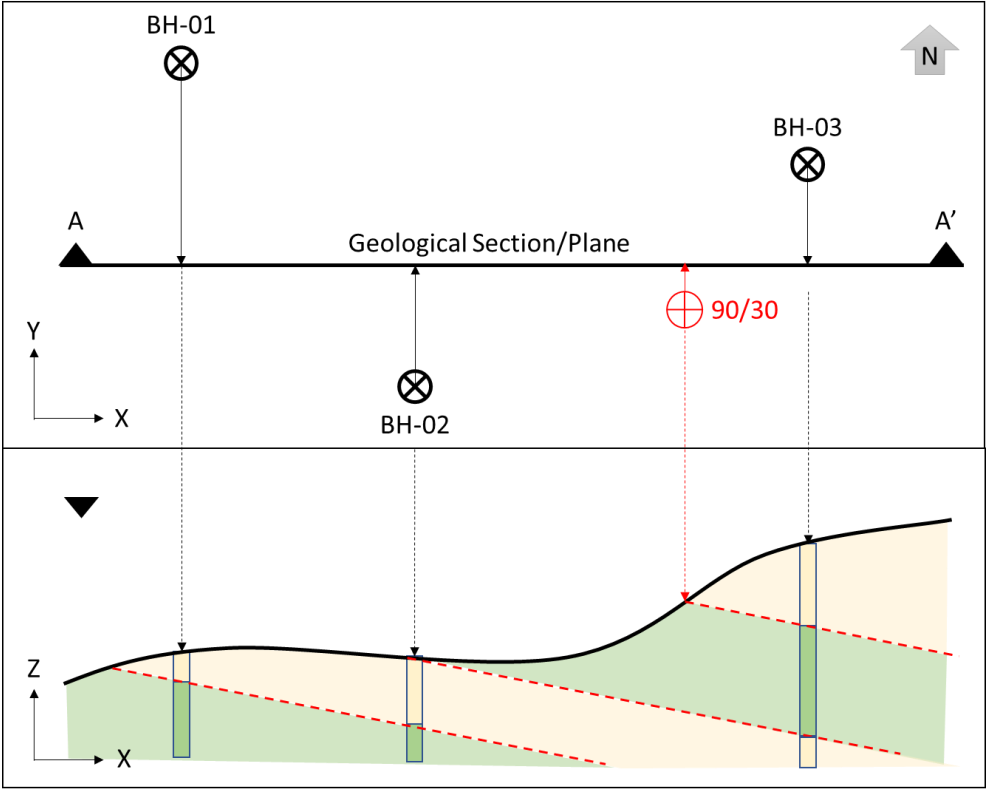


Figure 3-4. Linear interpolation and geometric projections from 2D geological representations.

In response to the complexity of the geology, especially in large-scale projects, and the amount of data to manage, some digital tools have been developed with the purpose of data management and 3D modelling achieving preciser and more accurate geological representations.

Nowadays, there are many options of software available in the market to produce geological/geotechnical models. Some were designed exclusively for geological 3D modelling as Leapfrog Geo (Figure 3-5), and others are analysis tools that integrate modeller functionalities as is the case of Bentley's PLAXIS 3D and Rocscience RS3 (Figure 3-6).

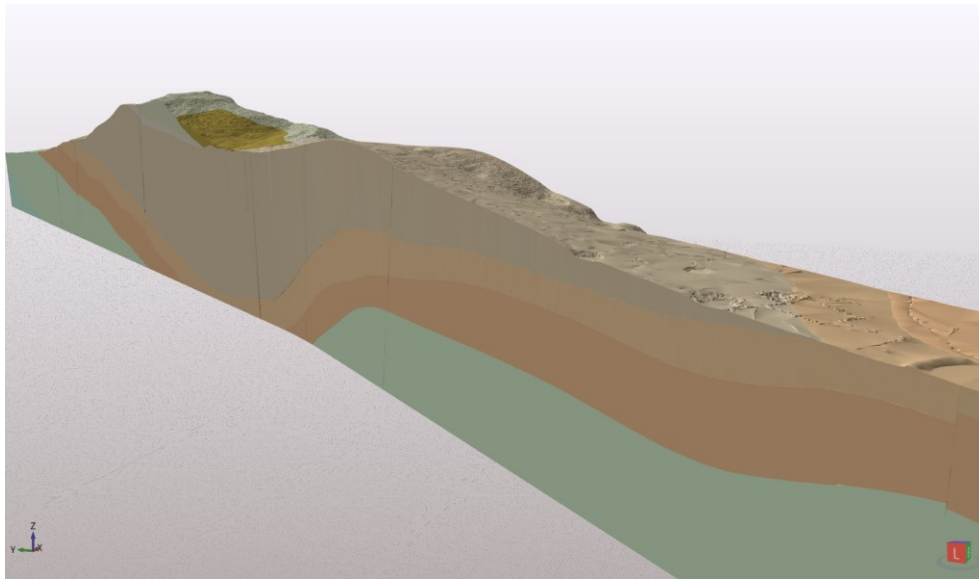


Figure 3-5. Leapfrog Geo Geological 3D Model [12].

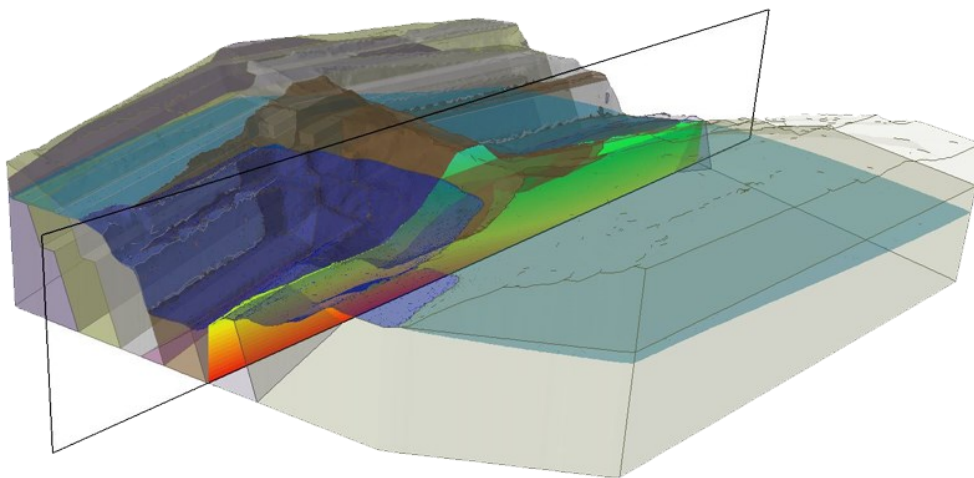


Figure 3-6. Rocscience RS3 Geological 3D Model[19].

The two main benefits of using digital tools for geological/geotechnical 3D modelling are the integration of databases in the process to manage a big amount of data efficiently and the usage of better interpolations methods as the inverse distance, Gaussian, among others (Figure 3-7).

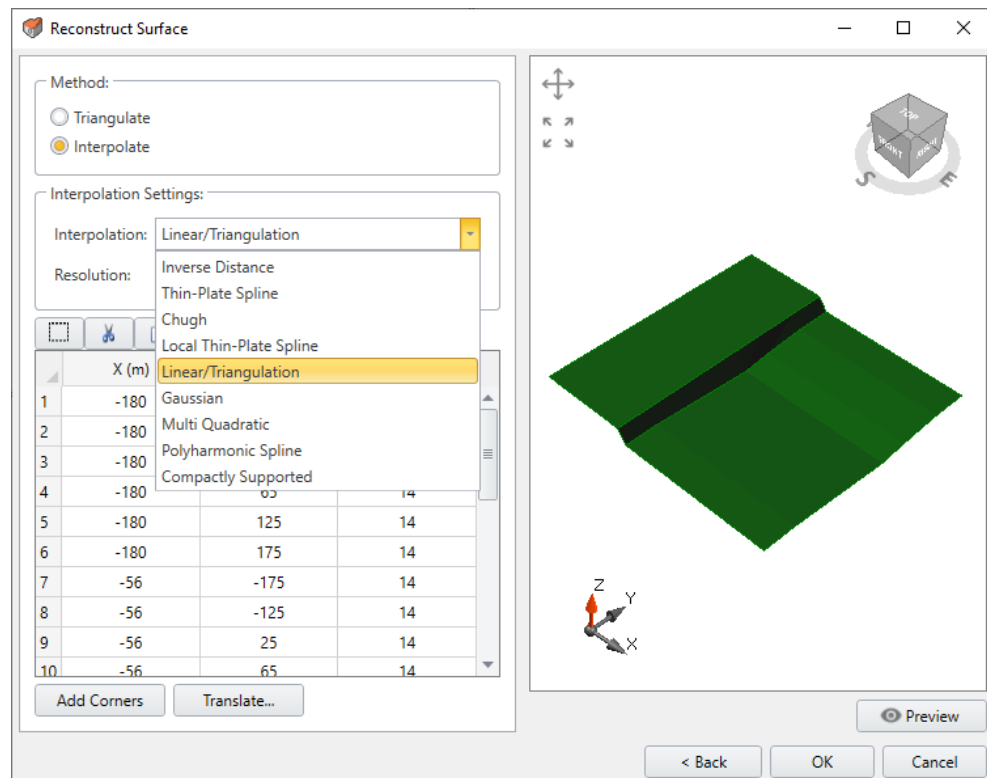


Figure 3-7. Rocscience RS3 Surface reconstruction [19].

In the BIM process, data management is critical. 3D modelling tools allow handling large-scale models where the complexity and variability in the geometry are high and the data to manage is vast. For tunnels, the geology is fundamental during the complete project's life-cycle, making so important the accuracy and precision in the geological/geotechnical model.

Nowadays, geological models are used usually for visualisation, coordination and quantity take-off. However, besides these uses, there are many potential uses to explore as the interoperability with analysis software, data management during the construction phase and geotechnical instrumentation integrated model.

In the frame of this document, more in-depth exploration about two common tools for geological/geotechnical model is shown below.

3.1.1 Leapfrog Geo

Leapfrog Geo enables the rapid construction of conceptual 3D models directly from a scattered borehole and GIS data sets without the need for manual digitisation. Leapfrog Geo uses implicit modelling to create geological models using a fast 3D interpolation technique to construct 3D boundary models from borehole data [20].

Explicit modelling is considered the traditional manual method of wireframe modelling and digitisation. Implicit modelling is an automated formation of surfaces such as inclination, faults and alteration directly from geological data. Leapfrog uses the implicit modelling method of geological modelling, which has rapidly gained acceptance worldwide because it considerably speeds up the modelling process and allows models to be updated automatically when data adjustments are made. Radial Basis Functions (RBF's) are the primary method to do this, but they have their limitations. After years of research, the algorithm FastRBF™ was developed. The main difference between traditional RBF's and FastRBF™ is the ability to process extensive data sets of well over 1,000,000 points incredibly fast on ordinary computer hardware. FastRBF™ also has exceptional extrapolation capabilities, even when significant gaps occur in a data set [21].

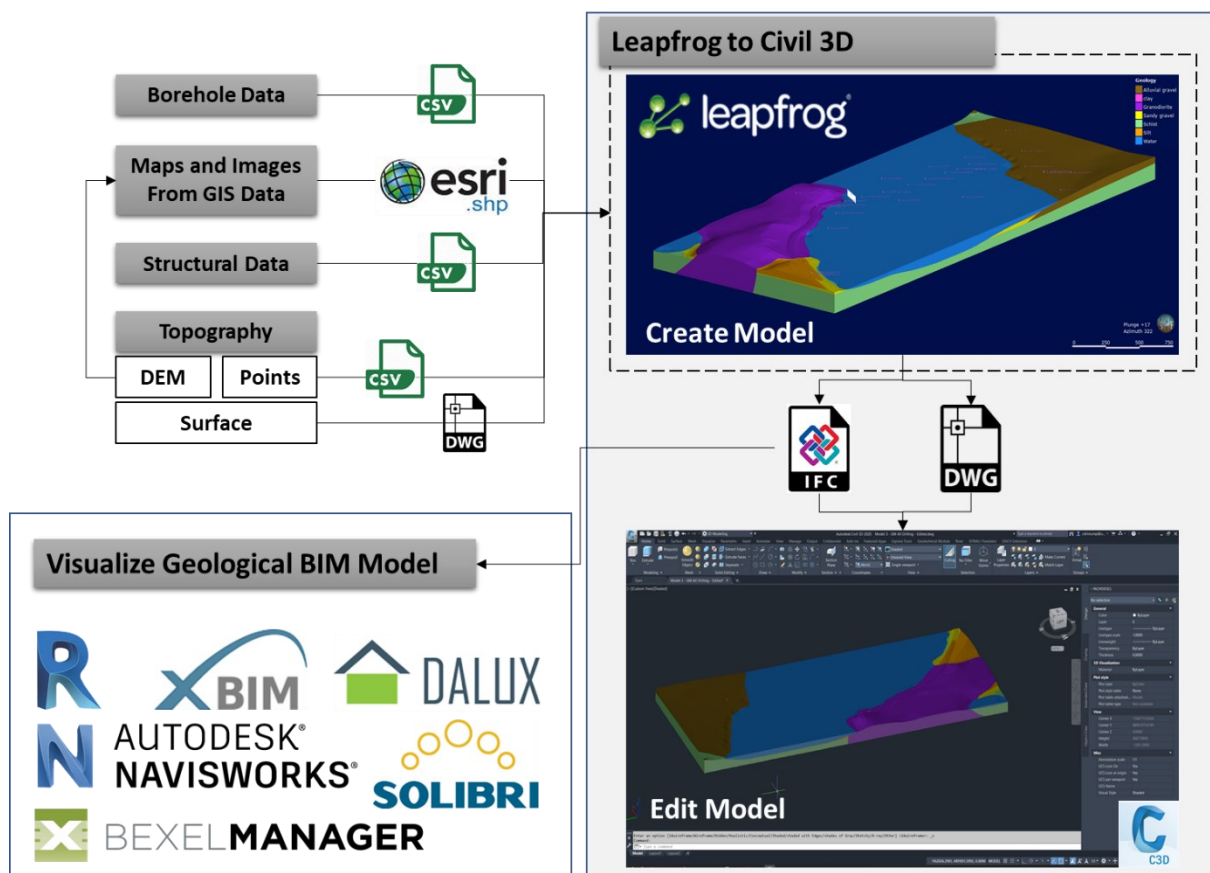


Figure 3-8. Leapfrog Interoperability Schema.

As is illustrated in Figure 3-8 Leapfrog includes extensive interoperability functionality for importing and exporting data. It is possible to import data from any GIS software, as maps, orthophotos, Digital Elevation Models (DEM) using shape files (.SHP); the discontinuity measures can be imported from a text file (.CSV); surfaces can be imported as .SHP, .DWG or CSV files and the borehole data can be taken from a database as a CSV file. It is important to mention that all these files remain linked to the central model, allowing to update the data easily.

The output data have two primary purposes, the first visualisation, in terms of BIM, the model can be exported as an IFC file to be integrated into a coordination model; and the second, to be used as a primary source of geometry to generate analytical models by exporting the model as a .DWG file or a mesh file (.MSH). In this second case, the capabilities of Autocad Civil 3D to manipulate and operate 3D models have proven to be trustworthy.

In tunnelling projects, as they are large structures, it is essential the capability of operating the geological model to create single geotechnical models extracted of the primary model. To manipulate the model is vital to understand the type of geometry exported from Leapfrog Geo. As was mentioned, there are two options by type of file (.MSH or .DWG). Mesh files usually can be read in any pre-processor or modeller from analysis software. Each layer or strata from the model is exported separately in a single file. The mesh is built by triangulated elements (Figure 3-9). For larger models, it is not recommendable to work with mesh files, as they contain a significant amount of elements that make difficult to work with in analytical software modellers. The best option is to work with the .DWG file that would contain the geometry as 3D solids, in a single file that can be operated in Autocad Civil 3D easily.

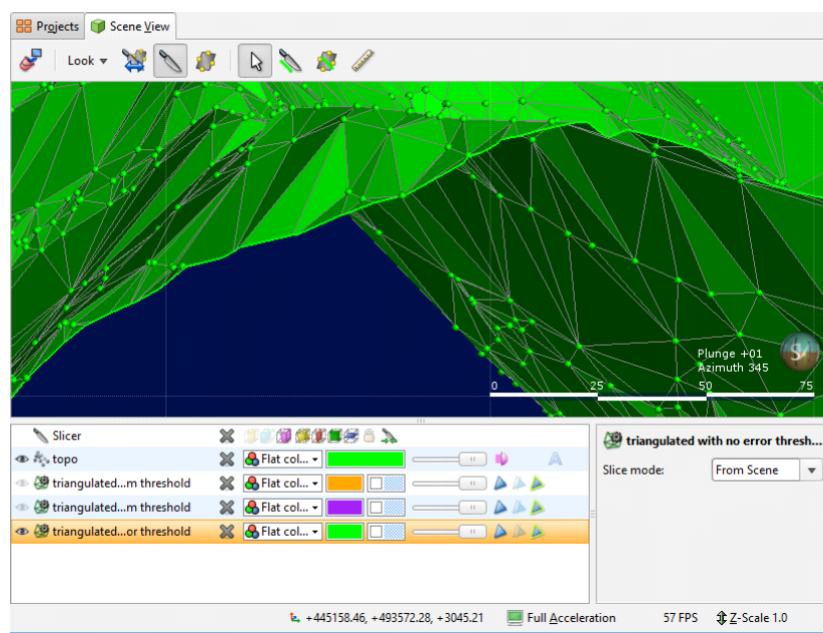


Figure 3-9. Leapfrog Geo Triangulated Mesh [20].

3.1.2 Autodesk Civil 3D: Geotechnical Module

The Autodesk Geotechnical Module is a plug-in for Autocad Civil 3D, developed by Keynetix based in HoleBASE. Keynetix was acquired by Bentley, who integrated HoleBASE, KeyLAB, OpenGround Cloud and others into the geotechnical software suite. Therefore, the Geotechnical Module is the key to interconnect the geotechnical data management systems with the BIM process.

The module allows connecting to a database that contains the borehole data as locations, strata depth and descriptions. The data can also be imported from a CSV file. Once the boreholes are imported, they will be represented graphically in the model. The basis of the module is to use the native surface generation of Autocad Civil 3D, using the points that represent the interfaces in the boreholes. It means the module creates the surfaces of the soil layers as triangulated surfaces using the shortest distance as criteria to generate the triangular elements. From the surfaces, it is necessary to check the correctness of the surfaces and edit them if it is required. However, it is important to mention that complex geology it is challenging to represent as is the case of rock masses where the plunge and trend are the principal characteristic and rule the geometry in the model, making no sense to use a direct triangulation between boreholes. The module was developed to create geotechnical models for quaternary deposits or soils, where the direct correlation between borehole make sense. When surfaces are correct, it is possible to create solids from the surfaces using the 3D modelling tools of Autocad Civil 3D. The created objects can be filled with properties and exported to any BIM software as an IFC file or .DWG in the case of Revit. The whole process is schematised in Figure 3-10.

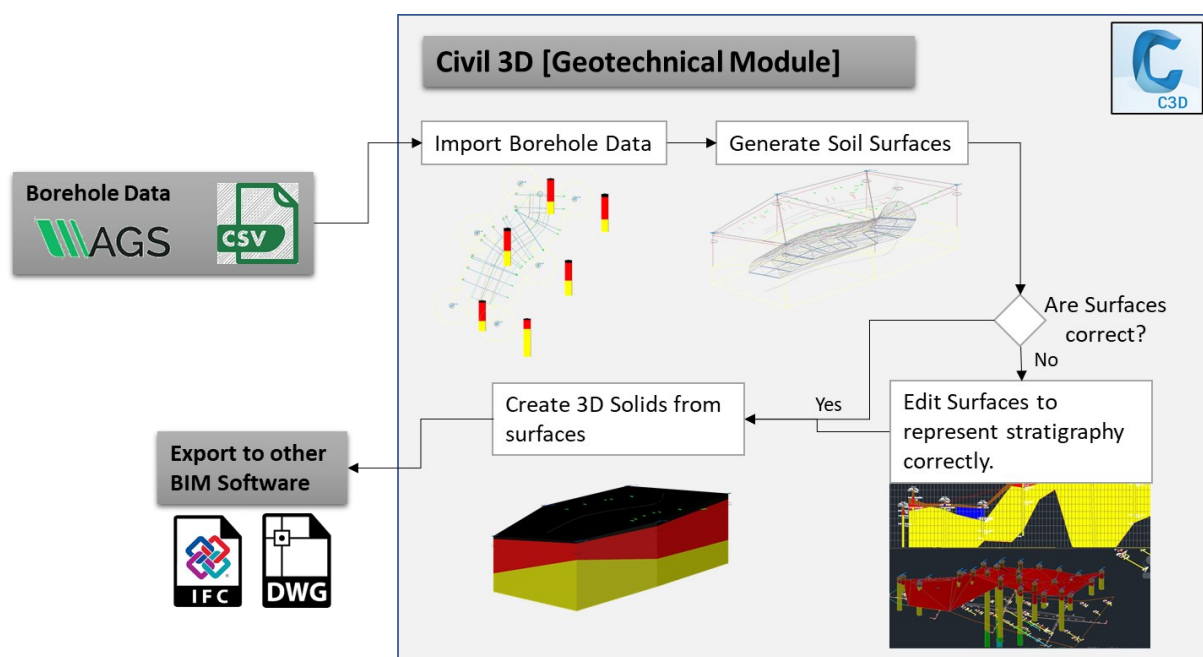


Figure 3-10. Civil 3D. Geotechnical Module geological model creation workflow.

3.2 Geotechnical Analysis

The generation of a realistic three-dimensional tunnel simulation model capable of representing the main components of a tunnel construction process requires considerable effort. In addition to the experience required to create an accurate numerical model, data from many different sources is required for the generation of a holistic simulation model. These data are usually not centrally stored and therefore, not easily accessible. Furthermore, the format in which the project data is stored is usually not compatible with the format required by the analysis software. This also applies to CAD data. Although existing design drawings are usually used as the basis for numerical analysis, direct import into a finite element program is often not successful because the imported data generates geometry that does not fully meet the requirements of the finite element model, such as model connectivity [11].

One of the potential uses of a 3D geological model is to create geotechnical models from a primary geological model. A geotechnical model is based on the geometry of the geological model, but layers can be grouped or split accordingly to the mechanical behaviour of the materials. Principally, the difference between both models, geological and geotechnical, is that the first is created based on the lithology and the second is created based on mechanical behaviour. Often the geometry is the same, especially in rock masses, but in large soil deposits, the case is different.

As was mentioned, tunnelling structures have constant interaction with the ground. This interaction is translated in ground deformation. In general, ground deformations in tunnels are caused by rock mass disturbance. The ground deformations caused by tunnel construction are mainly composed of three factors, namely geological factors, engineering factors and construction factors. Specifically, the geological factors mainly consist of rock mass grade, the Poisson's ratio of rock and soil masses, the angle of internal friction, joint development in the rock, soil moisture content, etc. The engineering factors mainly consist of the tunnel depth, the construction dimensions, the ratio of span to depth, the rigidity of the support, etc., while the design factors mainly consist of construction approach, the lining time, the excavation parameters, etc. Also, there is a significant interaction between the different factors [22].

The main scope of the geotechnical analysis is to design the supporting needed to minimise the estimated ground deformation. This ground deformation defines the theoretical tolerance between the shotcrete and the inner concrete, meaning relevant data for the quantity take-off and designing criteria. As more precise is the estimation of the ground deformation, fewer changes during the construction phase and more precise quantities can be expected.

In Figure 3-11 is shown the general workflow to perform geotechnical bidimensional (2D) and tridimensional (3D) analysis from a 3D geological model.

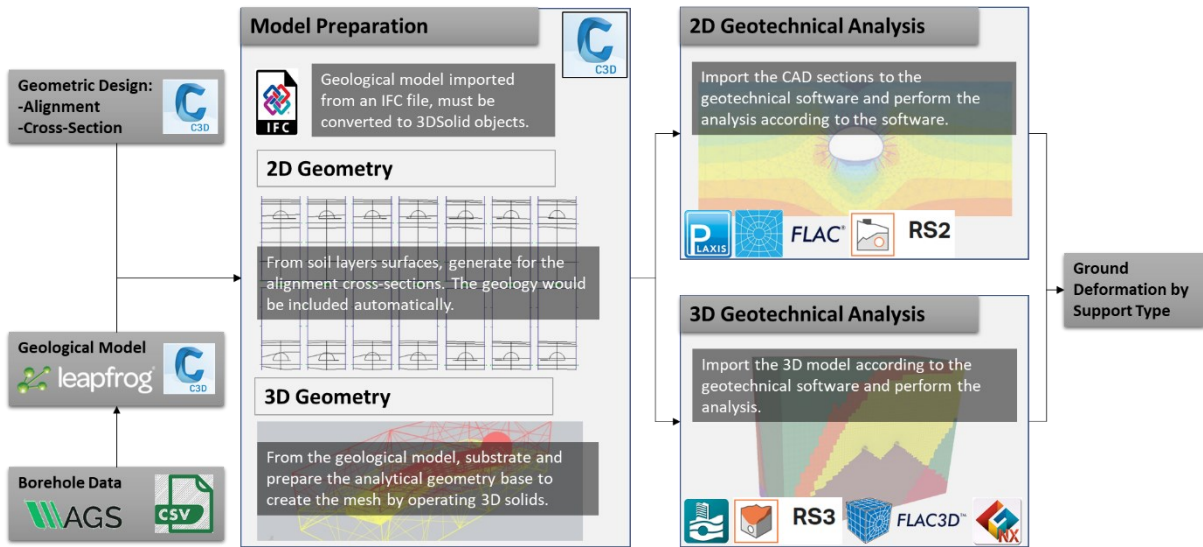


Figure 3-11. Geotechnical analysis from 3D geological models, general workflow.

Depending on the project, in some cases, it is enough to perform 2D analysis as the condition on the third dimension does not have significant variations. Furthermore, making a 3D geological model before is faster and better for the consistency between cross-section models. That creates two branches in the general workflow, one for the bidimensional analysis and another one for the tridimensional analysis.

3.2.1 Bidimensional Analysis

There are two main kinds of software in geotechnics for bidimensional analysis, depending on the method they use. The first kind is software based on the Finite Element Method (FEM), where the model geometry is used to generate a mesh that represents the analytical model. The second is the software based on the limit equilibrium method, where the model geometry is directly used as an analytical model. Limit equilibrium software is mainly for slope stability analysis which the scope is to determine the Factor of Safety (FS). Besides, FEM is a stress – deformation analysis where more conditions can be analysed, for example, settlements, slope stability, bearing capacity, excavations, among others.

In tunnelling structures, FEM is mainly used to design the supporting and calculate the ground deformation along the tunnel. Also, slope stability analysis is needed in the portal areas; in this case, can be made with FEM or limit equilibrium methods. Anycase, the workflow for making a bidimensional analysis from a 3D geological model is the same.

The 3D geological model must be imported in Autocad Civil 3D. The origin of the model is essential for this step because the surfaces that represent the soil interfaces are the source to generate the cross-sections. A model created with the Geotechnical Module of Civil 3D would contain these surfaces and 3D solids representing the ground layers. However, the model is created in Leapfrog Geo, would contain only 3D solids; the surfaces need to be extracted from the faces of the 3D solids.

In Autocad Civil 3D is necessary to have the tunnel alignment, corridor and geological surfaces. Using these objects as input data is possible to generate cross-sections automatically using the *Section Views* utilities of the software in the alignment; During the process, the corridor and geological surfaces must be selected. As a result, several cross-sections would be created containing the geological interfaces.

The cross-sections to be analysed have to be exported from Autocad Civil 3D to a drawing file (.DWG). From this file, the process depends on the analytical software to use because each one uses different conditions to import the geometry from a CAD file. For instance, Rocscience RS2 requires to difference and name by layers the external boundary and the material boundary, then export as DXF. The geometry is imported in RS2 using the DXF file, and the material properties can be assigned. RS2 have the tools to represent structural elements like concrete, bolts and geotextiles. The mesh generation tools are very well developed, allowing to densify the mesh in selected zones, avoid to create too small elements, and select different types of elements like three or six nodes.

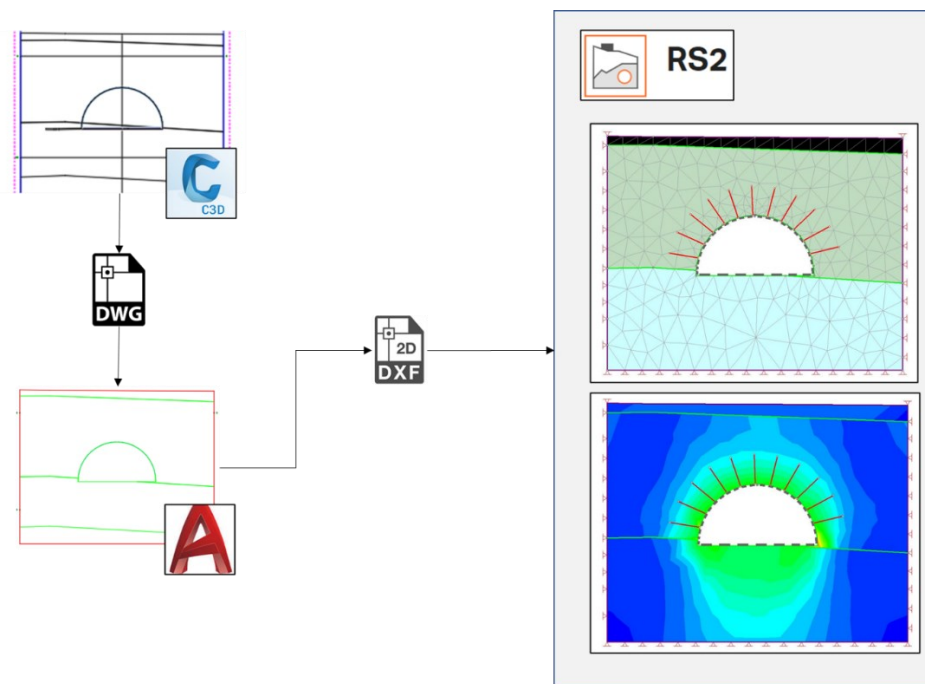


Figure 3-12. Rocscience RS2. Bidimensional Analysis.

PLAXIS uses python and considering that Dynamo and python are also available in AutoCAD Civil 3D, it is possible to translate soil parameters from the 3D model to the analytical model using a python script. Meshing is also available in AutoCAD Civil 3D, using native tools or Dynamo but meshing tools in most of the analytical tools are well developed and give more suitable options to generate better quality meshes.

3.2.2 Tridimensional Analysis

There are several options to perform a tridimensional analysis in a geotechnical software, like Rocscience RS3, PLAXIS 3D, Midas GTS NX, FLAC 3D among others. With the increasing usage of BIM, developers have been including one-way interoperability functionalities in the software. The case of Rocscience and Plaxis is possible to import the geometry directly as 3D Solids or surfaces from a DWG file. Notably, in PLAXIS 3D an IFC file of the structure can be imported, for analysis involving the real shape of the structure.

The workflow for a tridimensional analysis is quite simple, as most of the software allows to import volumes or 3D solids from a CAD file. Nevertheless, there are some important considerations:

- **Model Extension:** Usually, the best approach to create the geological model is to do larger sections or the whole model if possible, to consider the maximum amount of information at once. However, for the geotechnical model, is better sectioning the model in smaller models that represents typical or critical conditions to be analysed in order to produce a mesh which the computation time could be handle. Even though computers nowadays can process a significant amount of data, it does not mean that it is better to have larger meshes, but smaller high-quality meshes. From the whole geological model, sub-models must be subtracted. For tunnels, the extension of the model is controlled by the tunnel cross-section, the rock bolts length and the excavation steps. Even it is not necessary to have into the model all the ground above the tunnel, where the covering is high, and no stresses are expected in the surface. The submodel would be a square shape extrusion following the alignment segment of the tunnel. The side of the square should be at least two times the rock bolts length. In any case, the stress zone of the tunnel excavation and supporting system must be contained entirely in the model. It does not mean that the ground column above the tunnel is not considered in the analysis, it is, but as field stress in the analytical model.
- **Quality:** Sub-models are obtained mostly using boolean operations with the solids as union, intersection and subtraction. After this process, it is important to check the quality of the sub-model in order to detect possible intersections between objects, voids, too small objects or floating objects. The importance of this quality check is to avoid problems during the importation or meshing process.
- **Information:** The geological model objects must contain properties to identify the object, ground type and rock mass properties. This information can be lost using boolean operations between solids. For example, the resultant object of an intersection between a soil layer and an empty object (without properties) could be empty. Avoiding the data lost is vital in the case it would be translated within the geometry to the analysis software.

Mainly, the geotechnical software, as PLAXIS uses FEM. The basic equations for the static deformation of a soil body are formulated within the framework of continuum mechanics. A restriction is made in the sense that deformations are considered to be small. This allows a formulation regarding the original undeformed geometry. The continuum description is discretised using the finite element method. According to the finite element method, a continuum is divided into a number of (volume) elements, representing the model as a mesh (Figure 3-13). Each element consists of a number of nodes. Each node has a number of degrees of freedom corresponding to the discrete values of the unknowns in the boundary value problem to be solved. In the present case of the deformation theory, the degrees of freedom correspond to the displacement components [23].

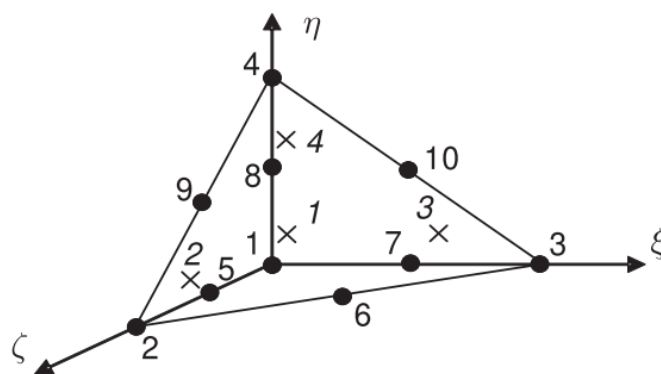


Figure 3-13. PLAXIS 3D. Tetrahedral Mesh [23].

Commonly, analysis software can be divided into three main parts; the pre-processor, that is the modeller tool or module of the software and also contains the mesh generation tools; the processor that is the module of the software that calculates and solve the mesh according to the mathematical formulation define in each software and; the post-processor that is the module that interprets the results to be visualised.

The integration of the geotechnical analysis tools in the BIM workflow consists of using the BIM or GIM tools as a pre-processor to create the geometry of the model except for the mesh generation. The mesh in any geotechnical software has particularities about formatting and information because even though the kind of mesh and method is the same, the mathematical formulation can be not the same. Further works can develop scripts to generate the mesh in BIM tools for every single geotechnical software. Nevertheless, it is essential to mention that the meshing tools of the analysis software are well developed in most of the cases.

A particular workflow was done for FLAC 3D, a software developed by ITASCA and commonly used to analyse projects where high ground deformation is expected. The difference between this software with others is that, it does not use the finite element method.

Instead, FLAC3D is an explicit finite difference program to study, numerically, the mechanical behaviour of a continuous three-dimensional medium when it reaches equilibrium or steady plastic flow. The observed reaction is derived from a specific mathematical model and a precise numerical implementation. The mechanics of the medium results from general principles (definition of strain, laws of motion) and the use of constitutive equations defining the idealised material. The resulting mathematical expression is a set of partial differential equations that relate mechanical (stress) and kinematic (strain rate, velocity) variables to be solved for particular geometries and properties under certain boundary and initial conditions. An important aspect is the inclusion of the equations of motion, although FLAC3D is primarily concerned with the stress and deformation state of the medium near the equilibrium state. The laws of motion for the continuum are transformed into discrete forms of Newton's law at the nodes. The resulting system of ordinary differential equations is then solved numerically with an explicit finite difference approach in time. The spatial derivatives involved in the derivation of the equivalent medium are those which occur when strain velocities are defined in terms of velocities. For the purpose of defining velocity variations and corresponding spatial intervals, the medium is discretised into elements with a constant strain rate of tetrahedral form, whose vertices are the nodes of the mesh [24].

FLAC 3D native modelling tools are script-based and not so well developed. To make easier the modelling process in the software, ITASCA developed a plug-in for Rhino named Griddle. The plug-in function is to convert a Rhino mesh into a FLAC3D mesh, allowing to use Rhino as a pre-processor. Using Rhino is also possible to import a geological model or sub-model from Autocad Civil 3D as a DWG file to generate the mesh for FLAC3d using Griddle (Figure 3-14).

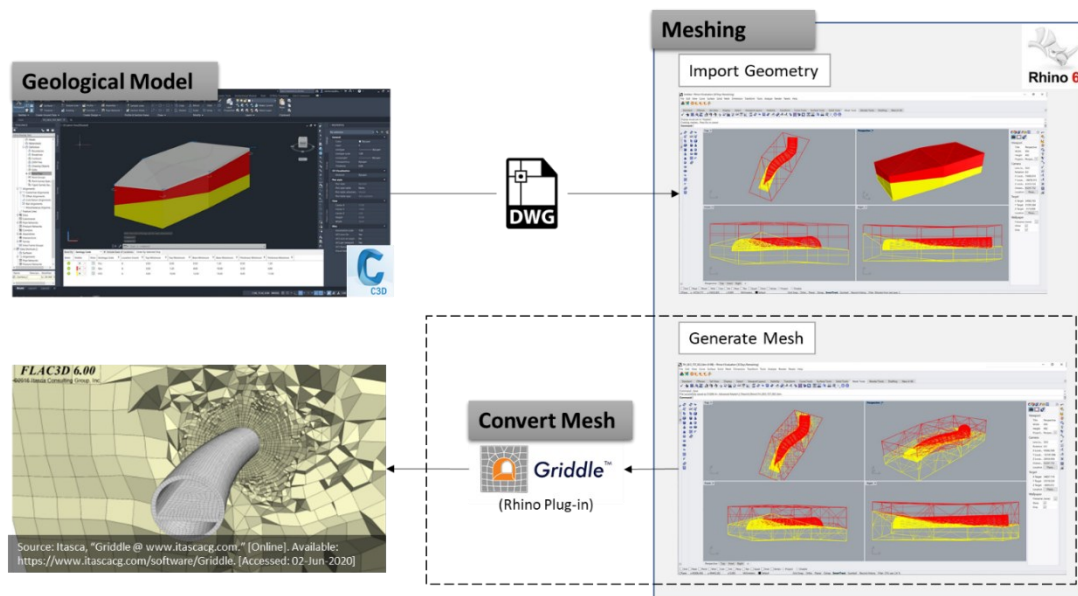


Figure 3-14. FLAC3D Mesh generation from a 3D geological model.

3.3 Geological Excavation Model

As was mentioned, the geological model has several uses in the BIM environment. However, a useful sub-model is the excavation model. Commonly, excavations are represented geometrically correct as a generic solid to measure the excavation volumes or to be used in a 4D and 5D simulation. The excavation model is the result of the interaction of the structure and the terrain to represent the earthworks.

Building and infrastructure models are usually made in modeller tools as Revit or Archicad, that does not have well-developed tools to model or work with ground models and does not have any predefined object category for it. Nowadays, the best approach is to use different tools as building-oriented tools, infrastructure tools and geological tools to produce high-quality models. This approach requires collaboration and interoperability that are the bases of BIM.

Excavation volumes are not the only important data from an excavation model, which material and its mechanical properties are essential during the construction phase. Depending on these properties, the excavation method is defined, and the unitary price is set. Moreover, in tunnelling structures, the kind of material, mechanical and rock mass properties are vital during the excavation. In tunnels, during the excavation process, strict control of the geology is required. Even though the geological model can be more precise and accurate using digital tools, still an interpolation based on a random sub-surface investigation. Changes about the location of supporting types along the tunnels are expected during the excavation. GIM and BIM integration reduce changes and their impact but do not eliminate it.

Established that geology is fundamental in the excavation process, it makes sense that geology should be represented in the excavation models. The geological model itself can not serve the purpose to fulfil the requirements about geological information during the excavation, because of its size. The geological model is created to represent the geology environment of the project. It means, a more significant extension of the project itself.

A useful model should be a geological excavation model (Figure 3-15) that represents the intersection of the geological model and the excavation model. The model still represents the shape of the volumes to be excavated and contains the information for the quantity take-off. For visualisation and coordination offer more information, for instance, to notice in a coordination model zones or ground materials to avoid. Faster navigation through the geotechnical information required for decision making during the excavation and construction phases. A proposal of the property sets (Figure 3-16) in the geological excavation model for tunnelling structures are:

- **Location Property Set:** Properties that allow for locating by a query a specific zone of the excavation. Must contain the support type considering that this is an essential criteria to divide or sectorise the model.

- **Quantity Take-Off Property Set:** In an excavation, the principal quantity is the volume. Could contain secondary quantities related to the excavation (transportation, workers, fuel, explosives, etc.).
- **Rock Mass Property Set:** Mostly tunnels are excavated in rock masses; however, excavations in soils are also frequent. In general, this property set must contain all the information about the geotechnical/mechanical behaviour corresponding to the theoretical constitutive model applied (Hoek-Brown, Mohr-Coulomb, etc.), classification and hydraulic properties, required for decision making during the excavation and construction phase.

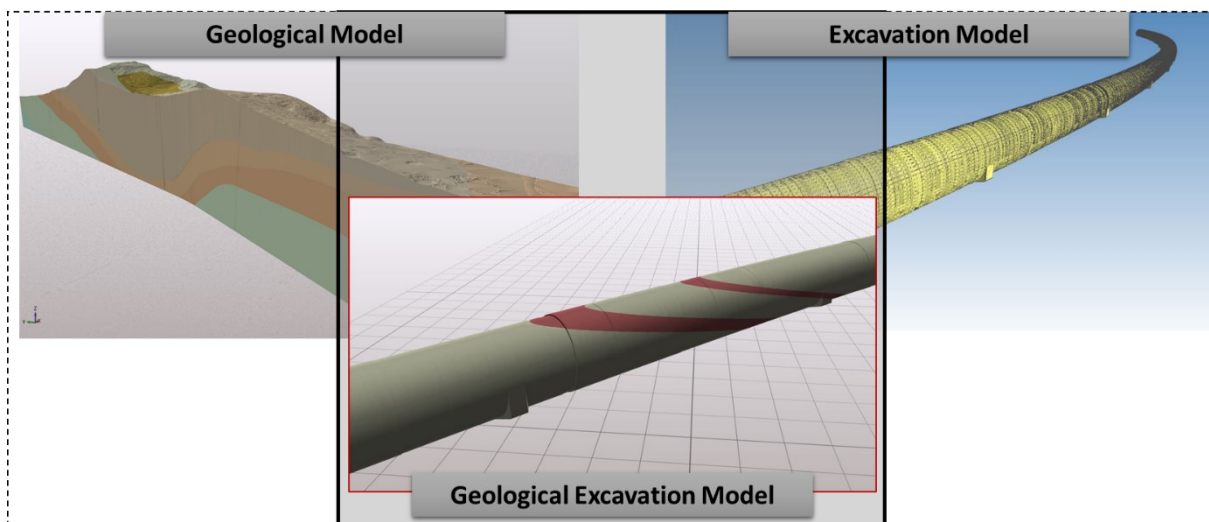


Figure 3-15. Geological Excavation Model.

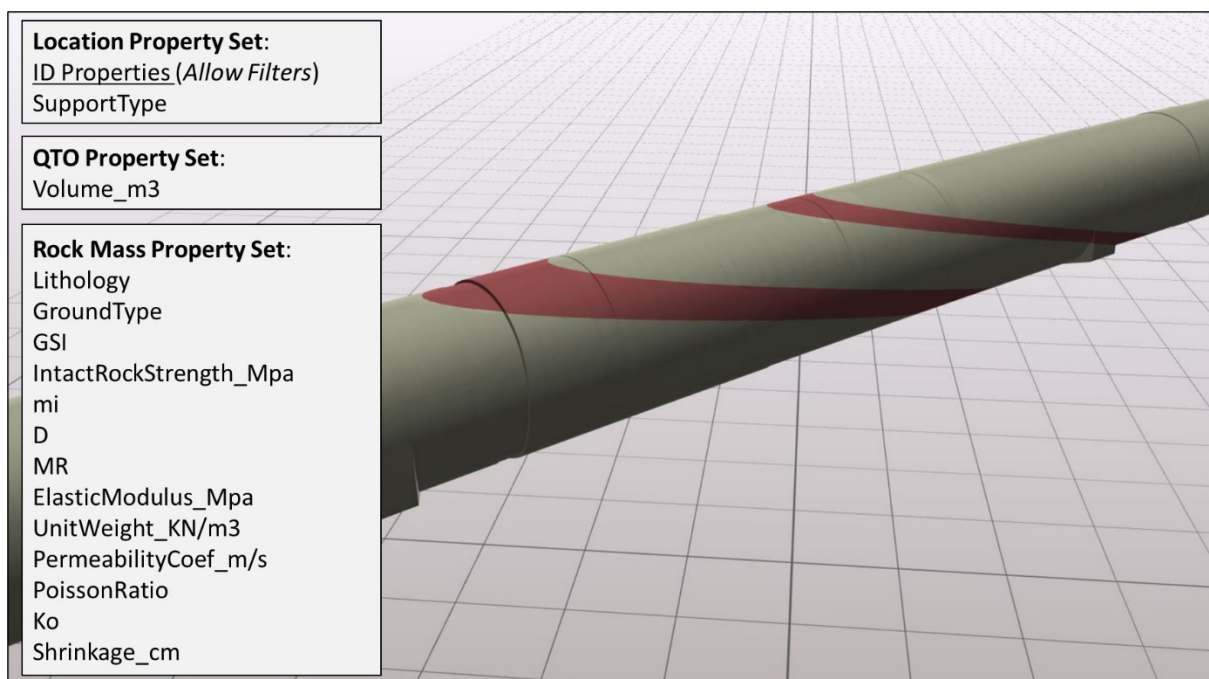


Figure 3-16. Geological Excavation Model Property Sets.

4 QUANTITY TAKE-OFF FOR TUNNELING STRUCTURES

The primary BIM use for infrastructure projects could be considered the quantity take-off. It is in the best interest of every investor to know the costs of a construction project in as much detail as necessary in order to be able to make economically sound decisions on the development of the construction works.

Quantity Take-Off (QTO) is a list of individual construction units taken from project documentation. It specifies the required quantities of work, construction, supplies, and services in units of measurement. It is expected to be clear, structured and verifiable. Even with the most modern means, it is almost impossible to achieve a perfect match of real and estimated baseline costs. The actual costs will only become clear after the project is completed. However, there are methods to bring actual and estimated costs closer together. Building Information Modelling (BIM) is one of them. A large part of the BIM model consists of databases that allow for the extraction of information. Quantity take-off may be one way of extracting information from a BIM model. The level of detail within the model can vary and should be contractually agreed. If the BIM model is efficiently linked to cost estimate system via partially automated quantity take-off, the role of the cost estimator in this process is greatly simplified [25].

While most BIM authoring tools are capable of performing the function of QTO but cost estimation, they are not able to do so, which is usually done by using different software. Since the QTO functions in these BIM authoring tools cannot usually be tailored to the needs of different countries, they must be adapted to meet certain criteria according to the requirements. Given these problems, there are several strategies for creating relevant solutions when developing applications for QTO and cost estimation. One of the strategies is to adopt a completely independent software into QTO and cost estimation applications development. This conversion process, which follows the openBIM strategy is very popular with current BIM applications for QTO and cost estimation. Its advantages are that the QTO and cost estimation is independent of the BIM authoring tools. Another strategy is to create a partially integrated software that integrates applications for QTO and cost estimation but needs to transfer data from BIM modelling environments. Applying propriety data schemas and modelling rules instead of using IFC for certain BIM authoring tools is a viable approach to avoid data loss for accurate QTO. Strategy 3 is also partially integrated, meaning software that QTO functions are adapted within the BIM authoring environments, and detailed results can be transferred to the separate cost estimation applications. About the QTO adaptation of BIM authoring or simulation tools that allows the extension of QTO functions by using an application programming interface (API) [26].

In this chapter is presented the general workflow and considerations to perform a quantity take-off for tunnelling structures and some specific considerations for the excavation and inner lining concrete.

4.1 General Division of the Model for QTO

Tunnelling projects are composed of two general kinds of structures; Single buildings, like stations, administrative buildings, portal areas; Lineal structures, that are all elements into the inner lining of the tunnel, as the support, shotcrete, railway or roadway, etc. This division is relevant to define the model, according to the Work Breakdown Structure (WBS). In the case of the single buildings, the element types are defined, and most of the objects represent a single part of the building. By the other hand, linear structures must be divided into several objects according to the supporting type and the pay items defined in the project's WBS.

Every object must have a location property set, which contains all required properties that allow filtering the model according to the WBS items. All the object's properties shall be specified in the project's BIM Execution Plan (BEP).

4.2 General workflow for QTO in Tunneling Structures

In general, the client prepare and share the WBS of the project, and it is considered by the designer to create the model. Therefore, the designer would provide to the estimator the model, usually in IFC format, and the WBS with an additional column indicating the property values to filter each item in the model. Also, the designer includes in all the model objects a property set for the QTO.

Taking into account that the WBS in tunnelling structures is based principally in the tunnel supporting types, the WBS of each project is different in items and categories; it is difficult to set a single template for several kinds of tunnels. Considering this particular condition about tunnelling projects is the best strategy for the QTO to use quantity and cost estimation software as Navisworks, Bixel Manager or Synchro. An alternative is to develop an API for the authoring software based in the property filtering, but it is important to mention that commonly infrastructure projects are made using various authoring tools for a single model.

Using a quantity and cost estimation tool, the estimator creates selection sets according to the WBS filters defined by the designer. These selection sets can be done manually or can be automatised using XML scripts to take the filter data from an Excel spreadsheet, as is the case of Navisworks. From the selection sets, it is possible to do the quantity take-off with a QTO property query.

It is essential to point out that some software can not measure directly from the geometry the quantities, just can read the stored property values from the objects. It means that all quantities must be stored as a property in all objects. Also, it means that it is not possible to check the veracity of a quantity value in this kind of software, because none of the geometrical properties are stored directly in the object or translated to the IFC file.

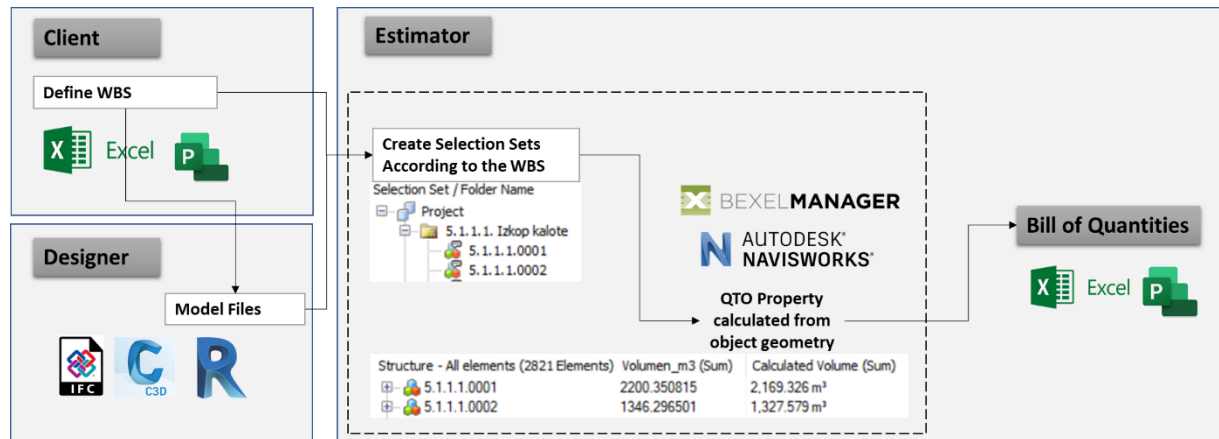


Figure 4-1. QTO for Tunnelling Structures General Workflow.

4.3 BIM Quality Control for QTO

The quality of the model is essential for the quantity take-off in tunnelling structures. While in simple projects a simplified representation of an object, with the correct properties can achieve a high-quality QTO, in infrastructure there are complex geometries that require a precise geometry representation. For example, a composed wall can be represented in a model as a single layer wall and contain properties to report every layer quantity precisely but, an excavation with a complex shape is better to measure the volume of the model object directly. Complex geometries are the reason to create LOD 300 model for the QTO. As is shown in Figure 4-2, a LOD 200 model for the inner lining is not enough to measure the excavation volume and the shotcrete area correctly, because the real shape of the excavation is simplified.

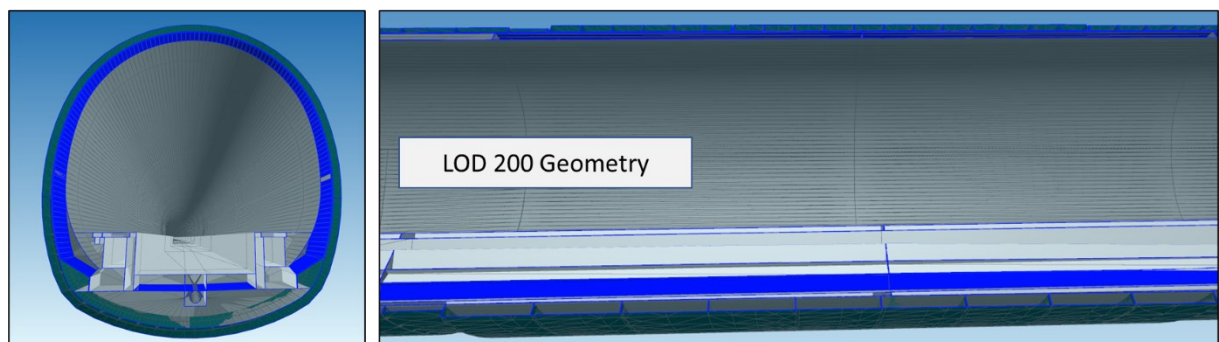


Figure 4-2. LOD 200 model for tunnel elements.

4.3.1 Excavation

As it was explained before, the excavation must be modelled from the theoretical line, which considers the construction tolerance and the ground deformation obtained from the geotechnical analysis. Even though the theoretical cross-section of the tunnel is a known shape and it is possible to calculate precisely the cross area, estimate the excavation volume as the product of this area and the excavation step length is not necessarily correct. Because the excavation model must be sectioned according to the excavation step, is important to notice in the vertical and horizontal curves that using a perpendicular line to the alignment centerline, the result is an overlap in the volume leading to an error in the quantification.

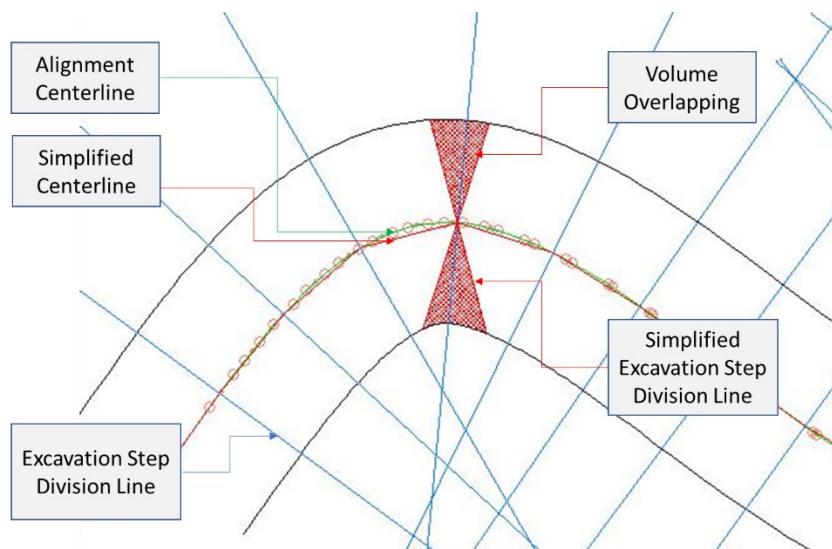


Figure 4-3. Overlapping volume in divided curve alignments.

To solve this inconvenience is better to make the quantification of the excavation volume using the native volume Calculation of the authoring tool. Most of the software calculates the volume as the summary of the mesh elements volume, considering that solids are also represented as a tetrahedral element.

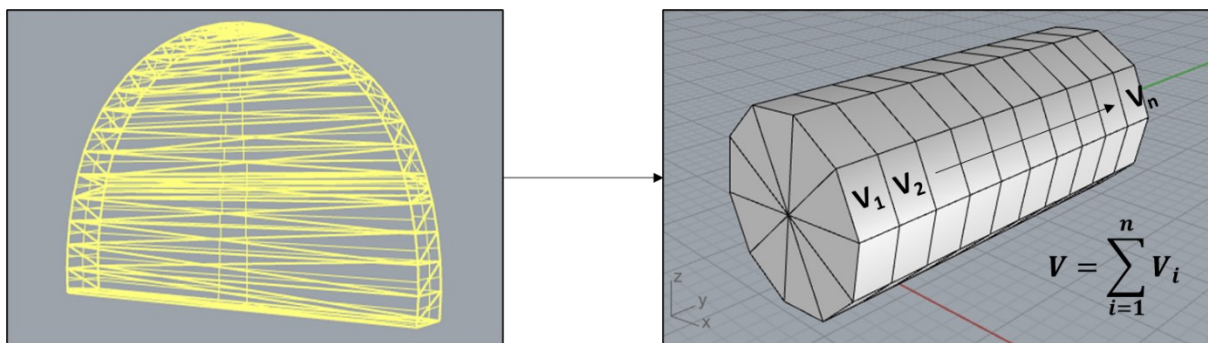


Figure 4-4. Native Volume calculation in BIM authoring tools.

4.3.2 Concrete

For the concrete parts of the tunnel, as the quantities are based on the concrete volume, the best approach is to follow the same technique as the excavation volume and use the native volume calculation of the BIM authoring tool. Besides, detailed quantities as the formwork need to be considered since the beginning in the creation of the parametric object, to be included as a property using the geometric parameters correctly.

Particularly, in the case of the shotcrete, it is common to measure this element by area for a specified thickness. In this case, the best approximation to the quantity is using the volume calculated by the software and divided by the thickness.

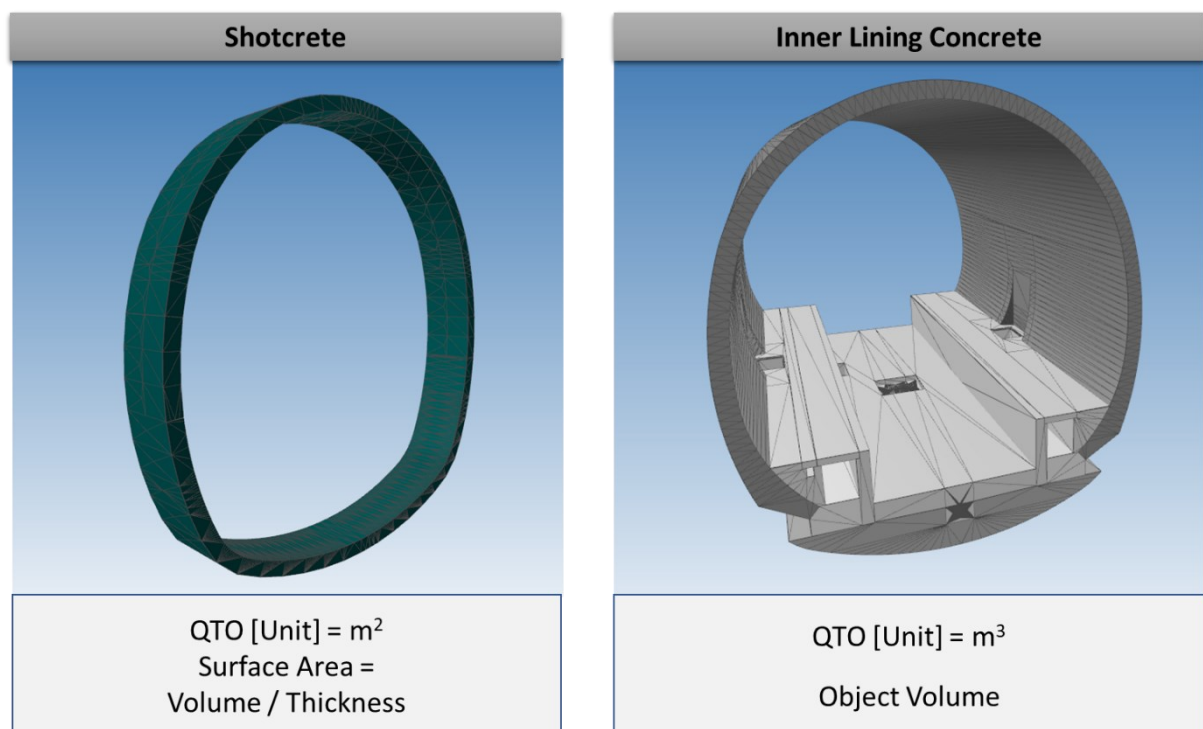


Figure 4-5. Concrete elements quantification.

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5 STUDY CASE: SECOND TRACK TUNNEL DIVAČA – KOPER (2TDK)

5.1 Project Description

The existing single-track railway line between Koper and Divača is the only railway connection between the port of Koper and the interior of the country. The capacity of the line is limited due to the technical equipment, and permeability and transportability are also affected by exceptional events and measures implemented on the line (such as overhauls and upgrades). Especially in the summer months, traffic is restricted by meadow and forest fires, which are often caused by flying sparks when trains brake on the tracks. Due to the nature of the terrain, landslides are also frequent. The Second Track Tunnel Divača – Koper (2TDK) is an integral part of the Trans-European Transport Network and extends between Divača and Koper, both situated in Slovenia. The current tunnel track was selected according to the highest criteria of environmental impact, safety, speed and traffic flow. The Second track will be a 27.1km long new railway line from Divača to Koper, which will include eight tunnels, two viaducts, two bridges and one gallery. 20.5 km or 75% of the line will consist of tunnels [27]. The general layout of the project is shown in Figure 5-1.

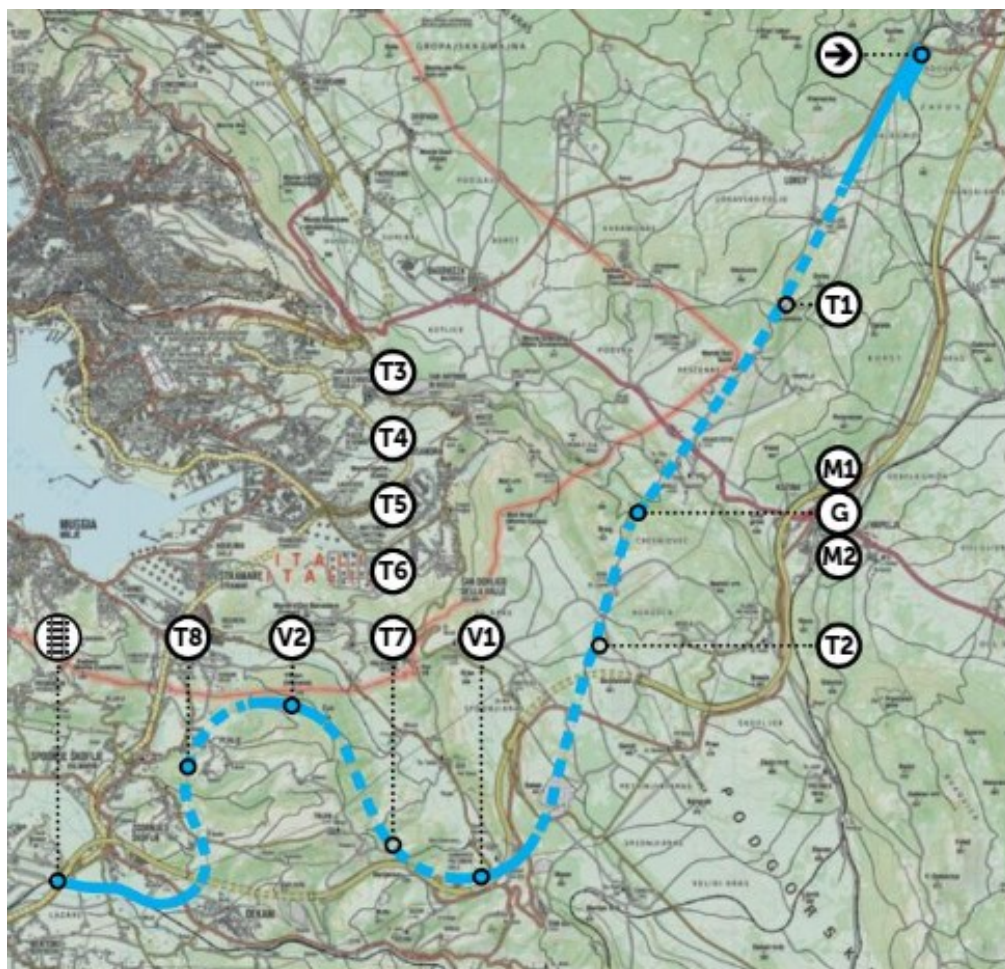


Figure 5-1. Second Track Tunnel Divača – Koper location.

5.2 QTO Review and Results

Consist in a general review of the first version (April, 2020) quantity take-off done by the designer for Tunnel 4 and 8 of the 2TDK project, specifically the items related with excavation and primary support concrete. For the review, the BIM model of tunnel 4 and 8 were available in IFC files. Tunnel 4 was exported from Revit 2020, while Tunnel 8 was exported from Autodesk Civil 3D 2020. Finally, the designer's bill of quantities was available in an Excel file.

The workflow consists of doing the quantity take-off whole process in a 4D and 5D BIM tool, based on the Work Breakdown Structure (WBS) defined by the designer in the Bill of Quantities (BoQ) and compare the results of this process in an Excel report. The workflow schema is shown in Figure 5-2. In this case, as BIM manage tool was used Bexel Manager because it is possible to calculate quantities from the object geometry, allowing to verify if the value of the property created by the designer is consistent with the geometry of the object. That is important since the native files of the BIM model are not available, so it is impossible to check all the rules and parameters used to create the geometry of the objects and fill the QTO properties.

Autodesk Navisworks Manage could be utilised instead as BIM 4D and 5D tool, with the limitation that this software does not calculate quantities from the object's geometry but from the properties within the object. This limitation makes it difficult to verify the consistency between the object geometry and the QTO properties values.

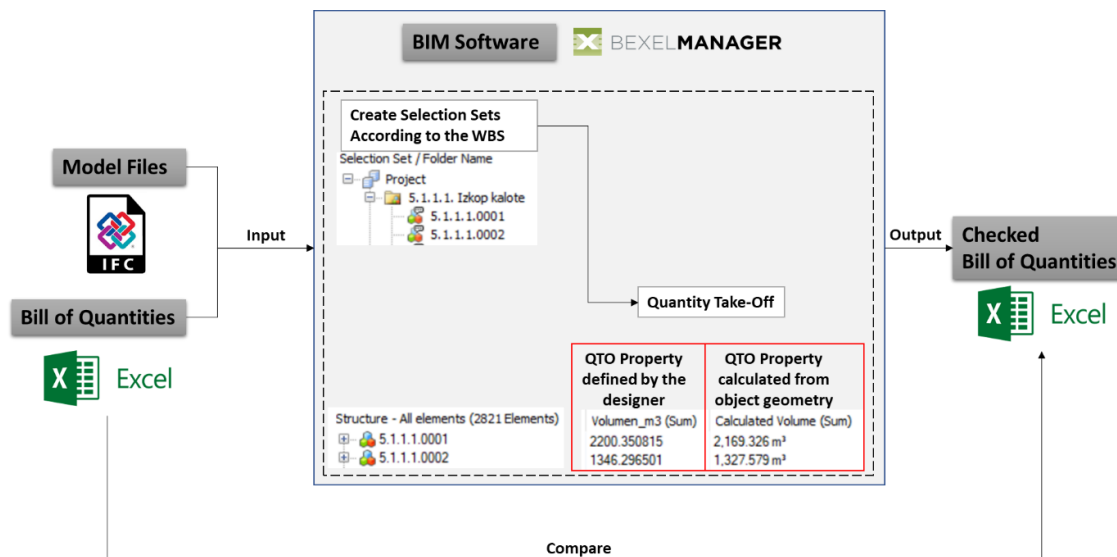


Figure 5-2. 2TDK QTO Review workflow.

As an alternative, another possible workflow is using a BIM Tool to export an excel file with all the object's properties and values and use it as a database to obtain the QTO values using the filter criteria

defined in the WBS by the designer. This alternative workflow schema is shown in Figure 5-3. The benefits of this workflow are:

- Less time consuming: Working on excel with all the data as a database is faster than set the query in a selection set than Navisworks or Bexel Manager.
- Non-BIM users friendly: Allows people without expertise in BIM software to work in the project with some Excel skills.

As the previous workflow, the limitation of Navisworks remains. Even though it is possible to export this excel file from both BIM tools, still better Bexel Manager where some calculated quantities would be exported as well.

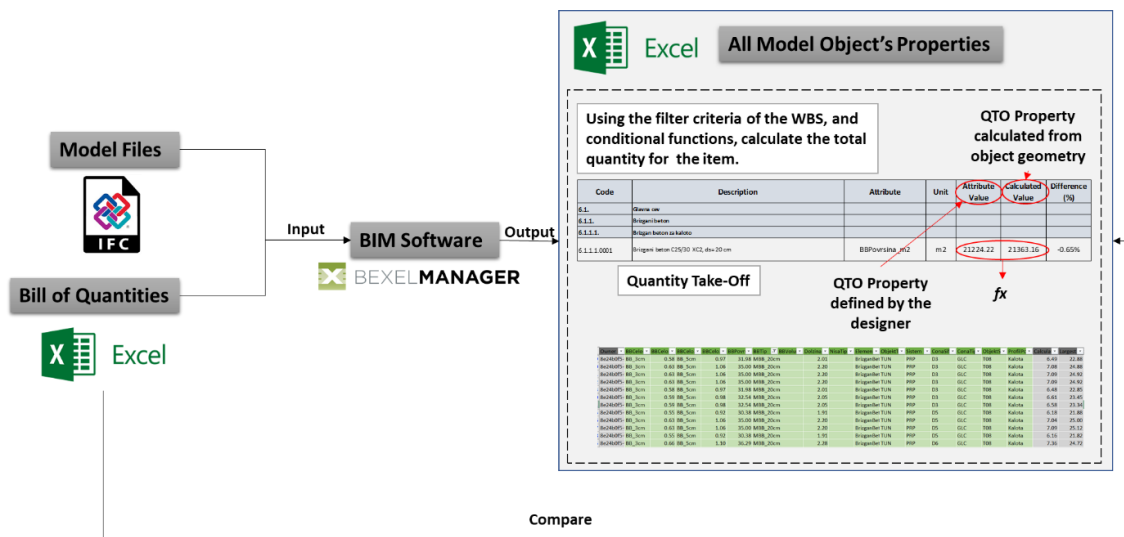


Figure 5-3. 2TDK QTO Review alternative workflow.

For the quantity review of the project, three values were considered; the calculated value, that is the quantity calculated by the software (Bexel Manager); the attribute value, that is the quantity value stored in the object; and the BoQ value, that is the value reported in the excel file of the BoQ. The review consists in to determine the percentage of the difference between the calculated value and attribute and BoQ values, according to the following expression:

$$\%Dif = \frac{CV - VTC}{CV} \times 100$$

Where,

%Dif: Percentage of the Difference

CV: Calculated Value

VTC: Value to check. (Attribute Value or BoQ Value)

5.2.1 Tunnel 4

5.2.1.1 Excavation

The model is composed of three IFC files and has a total of 3224 objects or elements, as is listed in Table 5-1 and a general view of the model is shown in Figure 5-4. All elements in the model have correctly assigned the QTO properties and their values.

Table 5-1. Amount of elements by IFC file in Tunnel 4 Excavation model.

| File | # of Elements |
|-------------------------------------|---------------|
| 2TDK_LEA_PZI_TUN_T04_Izk_GLC_XX_001 | 2942 |
| 2TDK_LEA_PZI_TUN_T04_Izk_IzC_CA_001 | 93 |
| 2TDK_LEA_PZI_TUN_T04_Izk_IzC_CB_001 | 189 |

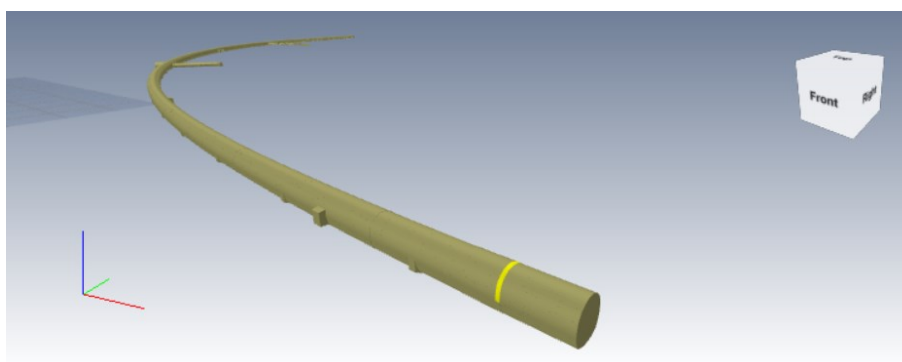


Figure 5-4. Excavation Model. General View. Tunnel 4.

In general, the quantity reported in the BoQ, the attribute value and the calculated value, had a difference below than 1% between them. All checked quantities are consistent.

5.2.1.2 Primary Support Concrete

The model is composed of three IFC files and has a total of 3267 objects or elements, as is listed in Table 5-2 and a general view of the model is shown in Figure 5-5. All elements in the model have correctly assigned the QTO properties and their values.

Table 5-2. Amount of elements by IFC file in Tunnel 4 Primary Support model.

| File | # of Elements |
|-------------------------------------|---------------|
| 2TDK_LEA_PZI_TUN_T04_PRp_GLC_XX_001 | 2985 |
| 2TDK_LEA_PZI_TUN_T04_PRp_IzC_CA_001 | 93 |
| 2TDK_LEA_PZI_TUN_T04_PRp_IzC_CB_001 | 189 |

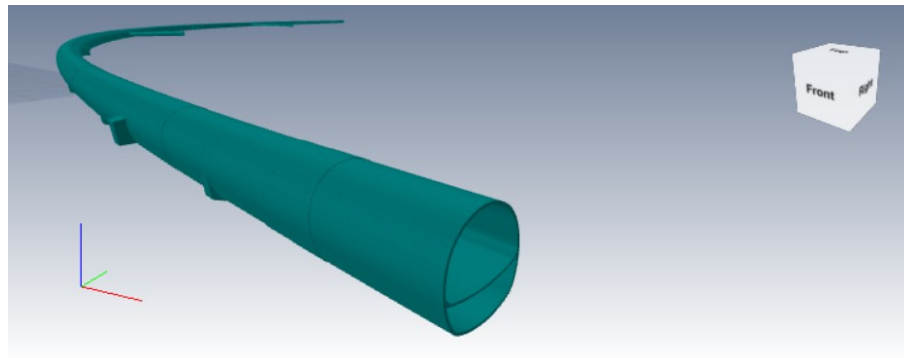


Figure 5-5. Primary Support Model. General View. Tunnel 4.

In general, the quantity reported in the BoQ, the attribute value and the calculated value, had a difference below than 1% between them. Still, some items have differences between 2 and 3% that should be checked. For the spread concrete, the reported value in the BoQ and the attribute value have differences up to 96%. Some of the quantity properties have inconsistent values between them.

5.2.2 Tunnel 8

5.2.2.1 Excavation

The model is composed of thirteen IFC files and has a total of 9133 objects or elements, as is listed in Table 5-3 and a general view of the model is shown in Figure 5-6. All elements in the model have correctly assigned the QTO properties and their values.

Table 5-3. Amount of elements by IFC file in Tunnel 8 Excavation model.

| File | # of Elements |
|-------------------------------------|---------------|
| 2TDK_IRG_PZI_TUN_T08_IZK_GLC_D1_001 | 751 |
| 2TDK_IRG_PZI_TUN_T08_IZK_GLC_D2_001 | 695 |
| 2TDK_IRG_PZI_TUN_T08_IZK_GLC_D3_001 | 726 |
| 2TDK_IRG_PZI_TUN_T08_IZK_GLC_D4_001 | 975 |
| 2TDK_IRG_PZI_TUN_T08_IZK_GLC_D5_001 | 721 |
| 2TDK_IRG_PZI_TUN_T08_IZK_GLC_D6_001 | 544 |
| 2TDK_IRG_PZI_TUN_T08_IZK_GLC_KO_001 | 2 |
| 2TDK_IRG_PZI_TUN_T08_IZK_PRC_XX_002 | 209 |
| 2TDK_IRG_PZI_TUN_T08_IZK_SRC_D1_001 | 775 |
| 2TDK_IRG_PZI_TUN_T08_IZK_SRC_D2_001 | 705 |
| 2TDK_IRG_PZI_TUN_T08_IZK_SRC_D3_001 | 724 |
| 2TDK_IRG_PZI_TUN_T08_IZK_SRC_D4_001 | 991 |
| 2TDK_IRG_PZI_TUN_T08_IZK_SRC_D5_001 | 744 |
| 2TDK_IRG_PZI_TUN_T08_IZK_SRC_D6_001 | 571 |

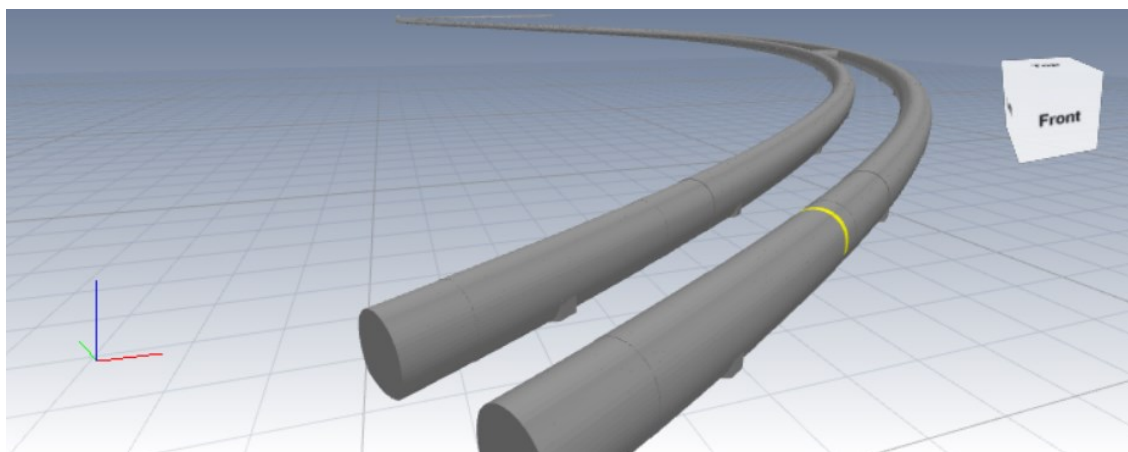


Figure 5-6. Excavation Model. General View. Tunnel 8.

In general, the attribute value and the calculated value had a difference between 1 and 13,5% while the difference between the calculated attribute and the value reported in the BoQ is up to 200% with an average of 30%.

5.2.3 Primary Support Concrete

The model is composed of thirteen IFC files and has a total of 9178 objects or elements, as is listed in Table 5-4. Amount of elements by IFC file in Tunnel 8 Primary Support model. and a general view of the model is shown in Figure 5-7. All elements in the model have correctly assigned the QTO properties and their values.

Table 5-4. Amount of elements by IFC file in Tunnel 8 Primary Support model.

| File | # of Elements |
|-------------------------------------|---------------|
| 2TDK_IRG_PZI_TUN_T08_PRP_GLC_D1_001 | 755 |
| 2TDK_IRG_PZI_TUN_T08_PRP_GLC_D2_001 | 695 |
| 2TDK_IRG_PZI_TUN_T08_PRP_GLC_D3_001 | 733 |
| 2TDK_IRG_PZI_TUN_T08_PRP_GLC_D4_001 | 975 |
| 2TDK_IRG_PZI_TUN_T08_PRP_GLC_D5_001 | 721 |
| 2TDK_IRG_PZI_TUN_T08_PRP_GLC_D6_001 | 547 |
| 2TDK_IRG_PZI_TUN_T08_PRP_SRC_XX_001 | 210 |
| 2TDK_IRG_PZI_TUN_T08_PRP_SRC_D1_001 | 796 |
| 2TDK_IRG_PZI_TUN_T08_PRP_SRC_D2_001 | 705 |
| 2TDK_IRG_PZI_TUN_T08_PRP_SRC_D3_001 | 731 |
| 2TDK_IRG_PZI_TUN_T08_PRP_SRC_D4_001 | 991 |
| 2TDK_IRG_PZI_TUN_T08_PRP_SRC_D5_001 | 744 |
| 2TDK_IRG_PZI_TUN_T08_PRP_SRC_D6_001 | 575 |

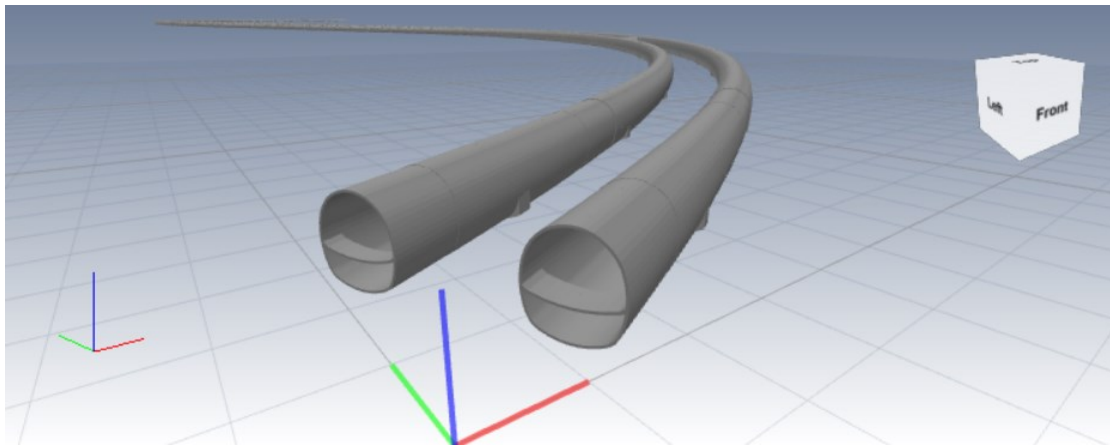


Figure 5-7. Primary Support Model. General View. Tunnel 8.

In general, the attribute value and the calculated value had a difference between 1 and 25% while the difference between the calculated attribute and the value reported in the BoQ is up to 200% with an average of 60%.

In Table 5-5 is reported the summary of the review of the quantity take-off made by the designer and presented in the bill of quantities.

Table 5-5. 2TDK - Quantity Take-off Review Summary

| Excavation | | | | | | |
|-----------------|------------|-------------|-------------------------------|--------------------|-------------------------|--------------------|
| Tunnel | # Elements | # WBS Items | Calculated Vs Attribute Value | | Calculated vs BoQ Value | |
| | | | # Items with Dif.> 1% | Average Difference | # Items with Dif.> 1% | Average Difference |
| | | | | | | |
| 4 | 3224 | 82 | 0 | 0.20% | 0 | 0.18% |
| 8 | 9133 | 106 | 78 | 4.13% | 91 | 10.20% |
| Primary Support | | | | | | |
| Tunnel | # Elements | # WBS Items | Calculated Vs Attribute Value | | Calculated vs BoQ Value | |
| | | | # Items with Dif.> 1% | Average Difference | # Items with Dif.> 1% | Average Difference |
| | | | | | | |
| 4 | 3267 | 83 | 36 | Note | 40 | Note |
| 8 | 9133 | 46 | 12 | 2.40% | 25 | 61.15% |

**Note: In this case, no elements were found in the model according to the item selection filter, but a quantity was reported in the BoQ.*

These differences are mainly due to values wrongly stored, either in the quantity or the location property set used to prepare the filters for the payitem in the BoQ; empty values and the procedure used to measure the volume in the objects. This review of the first version (April, 2020) of the model and BoQ, was presented to the designer, who took it in consideration to improve the model and BoQ for the next version.

Finally, during the review, is visible in this model, void gaps between objects as is shown in Figure 5-8, possibly due to issues with the script used to generate the model.

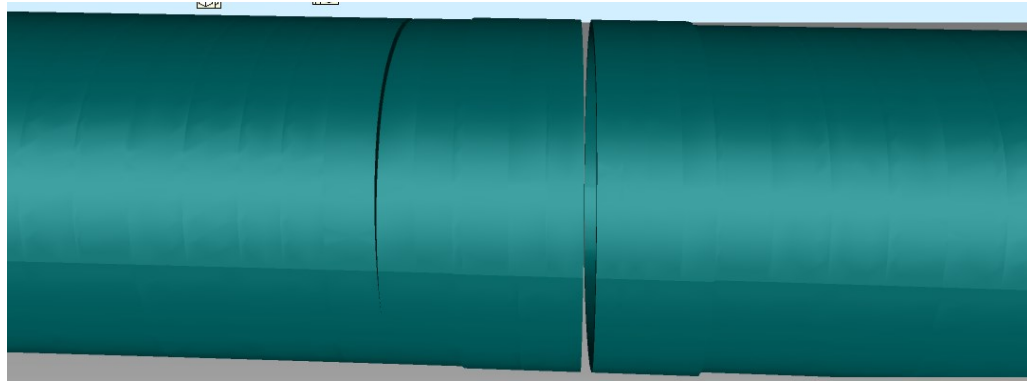


Figure 5-8. Voids between objects in Tunnel 8 Primary Support model.

5.3 Geological Excavation Model

Using the IFC file of the geological model made in Leapfrog Geo and the IFC file of the excavation model of Tunnel 8 a geological excavated model was done using AutoCAD Civil 3D. The model was filled with the properties shown in Figure 5-9 using the geotechnical information registered in the geotechnical report of the project.

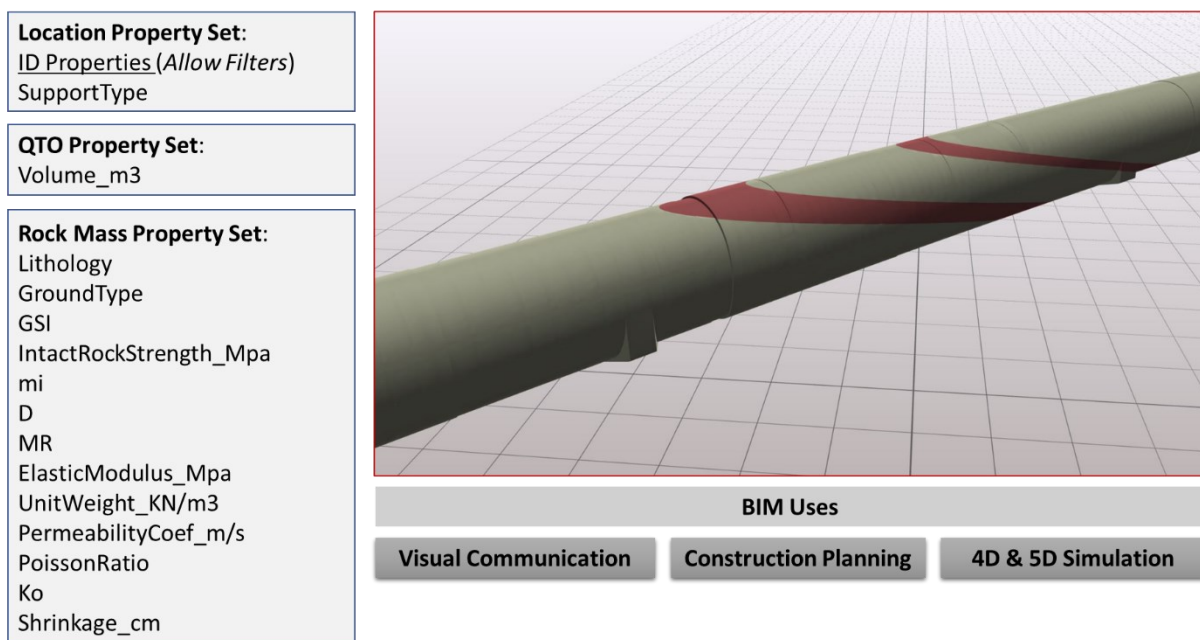


Figure 5-9. 2TDK – Tunnel 8. Geological Excavation Model.

This model was prepared as a tool for the geological – geotechnical information management during the excavation phase of the project, allowing to clearly understand the expected lithology in every excavation step, to reduce the communication lack in the decision making, highly required during this phase.

6 CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In tunnelling structures, the ground deformation is essential to be estimated during the design phase, and it would affect directly the quantities related to the excavation and the primary support system. With the increasing tendency of using BIM on infrastructure projects, like tunnels, the ground deformation must be included in the BIM process. It means the geotechnical workflow needs to be integrated into the BIM workflow.

With developing of new digital tools for geology and geotechnics, the concept Geotechnical Information Modelling (GIM) can be used to define the set of digital tools, workflows and standards for the collaborative management of geotechnical data during the project life-cycle.

Large-scale projects as tunnels require the management of a large amount of data collected during the project's life cycle. This data can be organised within a BIM model to facilitate access and collaboration in data management. Nevertheless, it requires to understand the particularities of tunnelling projects. A primary division (lineal or single buildings) in the models defines different workflows to be applied, and it consists of the differentiate the lineal parts and single buildings in the project. Single Buildings components can be identified in the latest IFC schema from BuildingSMART, while lineal components do not have a complete IFC schema definition yet. Due to this absence of IFC schema is necessary to define a property set that allows filtering the lineal objects of the model using the Work Breakdown Structure (WBS) as the primary source to split and identify the model.

According to the latest released version (4.1.0.0) of the IFC data schema, there are a few definitions for infrastructure that mainly consists of the usage of the element type *IfcCivilElementType* and the entity *IfcCivilElement*. However, the element type requires to use also an *IfcLabel* to describe precisely the type of element modelled.

The Level of Development (LOD) is a basic definition in the BIM Execution Plan (BEP) of the project because it determines the amount of details in the geometry representation and indirectly the precision of the quantities. As the IFC schema, nowadays there is not a standard about the LOD for infrastructure, but there some useful definitions for NATM tunnels as the one made by the German Committee for Underground Construction in 2019.

Geological modelling tools improves the accuracy in 3D representations, in comparison with 2D traditional representations, because of the capability of processing a significant amount of data as a complete set to generate a single geological 3D representation. A popular tool in Leapfrog Geo that allows creating complex geological models from different kind of data sources, as GIS data,

borehole data and CAD data. The interoperability with BIM tools is restricted to export the model as an IFC or DWG file; both cases only geometry is exported. The IFC file is useful only for visualisation, in a coordination view, considering that there is not an IFC schema defined for geology or geotechnical information.

Another tool for modelling is AutoCAD Civil 3D, with the geotechnical module it is possible to create non-complex geotechnical models, from a borehole data set. An interesting functionality of the module is the possibility of connecting to a database to acquire the borehole data. The modelling process is based on surfaces operations, making it harder to model complex geometry as a rock-mass where discontinuities also control the stratigraphy.

Every analysis software could be divided into three main parts: Pre-processor, processor and post-processor. The pre-processor is the tool used to create the model and the mesh, the processor is the tools that make the calculations from the mesh, and the post-processor is the tool to interpret the results. This thesis proposes to integrate the geotechnical process with the BIM process by using BIM tools as a pre-processor for the analysis tool. An answer to the modelling limitations of the analysis software, where geometry needs to be simplified in most of the cases.

Some interoperability tests were done using Rocscience RS2 and Itasca FLAC3D to successfully import the model geometry from a 3D geological model. The workflow consists of creating or modifying the model in AutoCAD Civil 3D; In the case of RS2, 2D geometry is acquired from the 3D model and exported as a DXF file and generate the mesh with RS2, for the imported geometry; In the case of FLAC 3D, the geometry created in Leapfrog or AutoCAD Civil 3D needs to be imported in RHINO, using a DWG file, to generate the mesh, then with a plug-in Griddle the mesh is converted into a FLAC3D mesh.

During these tests, research exploring the alternative to generate the mesh using BIM tools as Dynamo shows that it requires to be done for every single analysis software due to the characteristics of the mesh in each of them. Even though the geometry of the mesh can be created similar, the file structure of the mesh is different in any case. It means, the data, the matrixes, are organised in different ways, depending on the software developer. Nevertheless, considering that the native meshing capabilities of the analysis software are good enough, is an unworthy process to generate the mesh externally.

A geotechnical software research shows that tools like Rocscience RS3, PLAXIS 3D and Midas GTS NX, improved the capability to import external geometry, allowing to use BIM models for the analysis.

In tunnelling structures, an excavation model containing only volumes is not enough during the construction phase. Also, the geological model during the design phase is useful, but during the

construction could be difficult to understand. A proposal is to combine the excavation model with the geological model, to generate a geological excavated model, that represent the geology of the mass to be excavated. The model shall include a location, quantity take-off and rock mass property set, allowing the user to manage the geological and geotechnical information during the construction in a 3D environment more comfortable to understand.

In tunnels, the quantity take-off workflow has the main difference in how the model is divided. Buildings are commonly divided by stories and components (columns, beams, pipes, etc.), but in tunnels, the components are present in long distances. Because of this situation, the division of the model needs to be defined for every project in the BIM Execution Plan (BEP), considering the Work Breakdown Structure (WBS) defined by the stakeholders, the excavation steps and the supporting types defined by the geotechnical analysis.

For the quantity, take-off is necessary to define properties that allow filtering the model according to the pay items. These properties would be used to create selection sets in the BIM estimator tool to generate the bill of quantities. In consequence, these properties need to be adequately defined in the BIM Execution Plan (BEP).

Most of the quantities are based on the object's volume. So it is essential to measure this quantity correctly. There are different geometrical techniques to measure the volume from the shape, but considering the complexity of the objects in a tunnel, mostly because of the vertical and horizontal curves of the alignment, the best approach is take-off the volume using the native tools of the modelling tool, that is calculating the volume as the summary of the mesh elements volume.

A review of the quantities for the Second Track Tunnel Divača – Koper (2TDK) project, for tunnels 4 and 8 shows that 91 out of 106 WBS items have an average difference of 10.2% between the excavation volume reported in the bill of quantities and the calculated volume in the model. Also, for the primary support (shotcrete), 65 out of 129 pay items, have an average difference of 61.15 % in the concrete volume. These differences are because of the technique to measure volumes as well of issues regarding the property set used to create the selection sets. The designer took into consideration these results to improve the next version of the model and Bill of Quantities (BoQ).

6.2 Future Work

Considering the current development of the IFC schema for infrastructure, significant efforts are required to increase the element types in the schema, especially for tunnelling structures and geotechnical data. Furthermore, there are some exciting proposals of NATM tunnels IFC schema (see [16]).

Regarding the Level of Development (LOD) for tunnelling structures, a particular condition needs to be discussed with more detail for the shotcrete which the geometrical representation is variable in time because of the ground deformation. This discussion should be addressed in the context of standardisation for the LOD in NATM tunnels.

With the increase in digital tools development for geotechnics, especially for information management, is now possible to think about an integration of the geotechnical processes in the BIM workflow in the project life-cycle. This is especially relevant in infrastructure or large-scale projects, where geology and geotechnics define several aspects of the project. Further work must be done to standardise workflows for the geotechnical and geological information management and modelling in a BIM environment.

About the analysis software and BIM modelling tools interoperability, PLAXIS 3D includes the function to import the structure from an IFC file, to make preciser analysis including the actual data of the structure. Further research can explore the python functionalities of PLAXIS to import form a geotechnical BIM model, not only the geometry but the soils parameters as well.

The proposal of using the geology excavation model as a geological – geotechnical information management tool during the excavation phase of the tunnel, should be tested applied to real cases, to measure the variation of the lack of time in the decision-making process.

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ANNEX A: IfcCivilElement Property Sets For Objects

Source: Adapted from BuildingSMART [28]

| PsetName | Properties |
|--|---|
| Pset_ConcreteElementGeneral | ConstructionMethod, StructuralClass, StrengthClass, ExposureClass, ReinforcementVolumeRatio, ReinforcementAreaRatio, DimensionalAccuracyClass, ConstructionToleranceClass, ConcreteCover, ConcreteCoverAtMainBars, ConcreteCoverAtLinks, ReinforcementStrengthClass. |
| Pset_PrecastConcreteElementFabrication | TypeDesignator, ProductionLotId, SerialNumber, PieceMark, AsBuiltLocationNumber, ActualProductionDate, ActualErectionDate. |
| Pset_PrecastConcreteElementGeneral | TypeDesignator, CornerChamfer, ManufacturingToleranceClass, FormStrippingStrength, LiftingStrength, ReleaseStrength, MinimumAllowableSupportLength, InitialTension, TendonRelaxation, TransportationStrength, SupportDuringTransportDescription, HollowCorePlugging, CamberAtMidspan, BatterAtStart, BatterAtEnd, Twisting, Shortening, PieceMark, DesignLocationNumber. |
| Pset_EnvironmentalImpactIndicators | Reference, FunctionalUnitReference, Unit, ExpectedServiceLife, TotalPrimaryEnergyConsumptionPerUnit, WaterConsumptionPerUnit, HazardousWastePerUnit, NonHazardousWastePerUnit, ClimateChangePerUnit, AtmosphericAcidificationPerUnit, RenewableEnergyConsumptionPerUnit, NonRenewableEnergyConsumptionPerUnit, ResourceDepletionPerUnit, InertWastePerUnit, RadioactiveWastePerUnit, StratosphericOzoneLayerDestructionPerUnit, |

| PsetName | Properties |
|--------------------------------|--|
| | PhotochemicalOzoneFormationPerUnit, EutrophicationPerUnit, LifeCyclePhase. |
| Pset_EnvironmentalImpactValues | TotalPrimaryEnergyConsumption, WaterConsumption, HazardousWaste, NonHazardousWaste, ClimateChange, AtmosphericAcidification, RenewableEnergyConsumption, NonRenewableEnergyConsumption, ResourceDepletion, InertWaste, RadioactiveWaste, StratosphericOzoneLayerDestruction, PhotochemicalOzoneFormation, Eutrophication, LeadInTime, Duration, LeadOutTime. |
| Pset_Condition | AssessmentDate, AssessmentCondition, AssessmentDescription |
| Pset_ManufacturerOccurrence | AcquisitionDate, BarCode, SerialNumber, BatchReference, AssemblyPlace. |
| Pset_ManufacturerTypeInfo | GlobalTradeItemNumber, ArticleNumber, ModelReference, ModelLabel, Manufacturer, ProductionYear, AssemblyPlace. |
| Pset_ServiceLife | MeanTimeBetweenFailure, ServiceLifeDuration. |
| Pset_Warranty | WarrantyIdentifier, WarrantyStartDate, WarrantyEndDate, IsExtendedWarranty, WarrantyPeriod, WarrantyContent, Exclusions. |