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BIM Methodology Approach to Infrastructure Design: Case Study of Paniga Tunnel

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Abstract. Nowadays, the implementation of Building Information Modelling (BIM) in civil design represent a new challenge for the AECO (Architecture, Engineering, Construction, Owner and Operator) world, which will involve the interest of many researchers in the next years. It is due to the incentives of Public Administration and European Directives that aim to improve the efficiency and to enhance a better management of the complexity of infrastructure projects. For these reasons, the goal of this research is to propose a methodology for the use of BIM in a tunnel project, analysing the definition of a correct level of detail (LOD) and the possibility to share information via interoperability for FEM analysis.

1. Introduction

The BIM methodology is widely adopted in the building industry, and its spread is in continuous growth. The reasons of this success, from one hand is due to the incentive of Public administration such UK, Norway, USA, Singapore and etc. that improve the BIM adoption in AECO industry, in order to reduce the CO2 emissions by 80% by 2050 [1]. From other hand is due to the benefits of BIM adoption as the capability to create an information parametric model able to facilitate a better design, to enhance construction efficiency, to develop a collaborative approach, a better control of time and costs.

A McGraw-Hill survey [2] revealed that the North America had a BIM adoption rate of 49% compared with the rate of 36% of the Western Europe. In this scenario, the implementation of BIM for infrastructure shows a positive trend; in fact, from 2009 to 2013 the value of "no use BIM" among A/E (Architects and Engineer) is decreased from 73% to 0% [3]. Thus, this reveals a positive trend of BIM adoption not only for A/E but also for Contractors and Owners, forecasting a strong growth in the next years.

1.1. Related work

At the moment several studies are facing the challenges to testing BIM in infrastructure field, in order to provide a methodology able to manage a large amount of heterogeneous data. For this reason, it is necessary to find a way to collect the information in a unique interactive database, able to share information among different discipline. Stascheit et al. [3] proposes a tunnel product model composed basically from three sub-domain: I) the ground data model (GDM); II) the tunnel model (TM); III) and the tunnel boring machine model (TBM). In this way, it is possible collect information about the subsurface including ground layer and its material parameters. Furthermore, the TM storage

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information about tunnel alignment, lining segments and annular gap grouting. Instead the TBM model provides information about the dimension and the characteristics of each shield machine components. Related to the shield tunnel Yabuki [4] develops a IFC-shieldTunnel able to describe the soil layer and cave boundary in order to provide a geometric representation of underground soil and tunnel cave. Finally, the representation of a multiple scale in according with Borrmann and Jubierre [5] that developed a multi scale products model in order to combine semantic and geometrical aspects, through the use of specific LOD objects.

Basing on this background, this paper aims to propose a methodology to produce a tunnel product model (TPM), starting from the parametric model and setting of parametric library arriving to geotechnical analysis via interoperability.

The case study chosen for this work is Paniga tunnel inside the Morbegno's variant project. The tunnel has an overall length of 2323 m, from km 12+974 until km 18+297 it has approximately west-east orientation and cover values that vary from a minimum of 2 m to a maximum of 360 m. The tunnel is excavated in Gneiss of Morbegno and, for a short section, in the Granite of Dazio.

2. BIM for infrastructure design

BIM tools, as presented before, are not yet ready to generate optimal results in terms of accessibility and liability in infrastructure design. For these reasons, the goal of the research is to find a good methodology to apply BIM in the civil field, analysing the following relevant topics: I) Level of model definition; II) Objects library; III) Information exchange.

In order to develop this research, the parametric model of the tunnel and related components were modelled using Autodesk Revit software.

2.1. Level of model definition

One of the first objective in developing a BIM model of an infrastructure is to define its LOD. Design phase outputs required a very detailed definition of project components, in a way to enable the user to extract automatic schedules of elements quantities and related costs, but also to permit the generation of 2D technical drawings.

Starting from PAS 1192-2:2013[7] levels of model definition for building and infrastructure projects, it is possible to define LOD 4 as the level of development of this project (figure 1). In terms of parametric information, this level consists in an accurate modelling of specific systems, objects and assemblies in terms of specification, size, form, function and location.

2.2. Objects library

Currently BIM software are fully developed for vertical structures, while it is quite the opposite for projects with horizontal extension, such as infrastructures. This means a consistent effort in creating parametric elements and objects specifically for infrastructures projects.

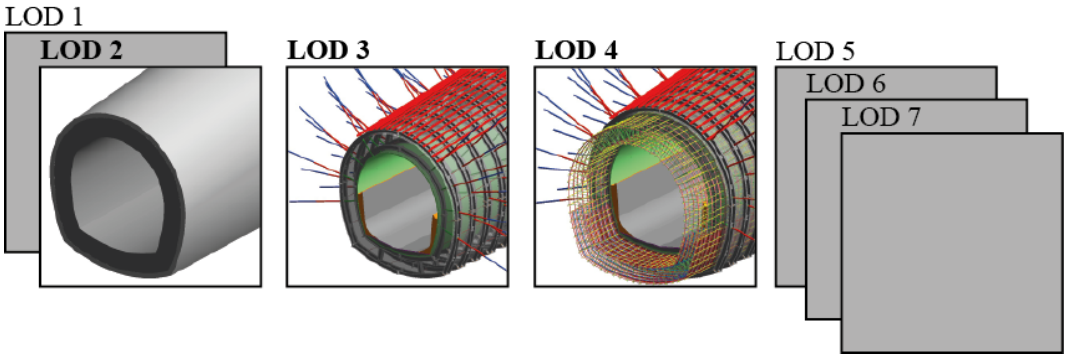


Figure 1: Level of model Definition designed for the case study of Paniga tunnel

BIM methodology benefits are represented by the possibility to I) visualize a 3D model, II) create fabrication/shop drawings, III) enable code reviews, IV) estimate costs, V) organize construction sequencing, VI) perform clash detection, VII) conduct forensic analysis, VIII) manage Facility Management operations [8]. The way to take advantage from the BIM methodology also in the civil field, is to create a series of family that use parameters to characterise intelligent constraints, relationships and interdependencies between project elements, and in particular between family types, useful to be adapted for different section types. Paniga tunnel is composed by six different section types, each one composed by different types of families, as resumed in Table1.

Table 1. Families created for each section type

Section Types and Families					
A0	**A1**	**A2**	**B1**	**B1F**	**Pre-tunnel**
Crown and spring lines	Crown and spring lines	Crown and spring lines	Crown and spring lines	Crown and spring lines	Crown and spring lines
Side walls	Side walls	Side walls	Side walls	Side walls	
Shotcrete layer	Shotcrete layer	Shotcrete layer	Shotcrete layer	Shotcrete layer	
Lean concrete layer	Lean concrete layer	Lean concrete layer	Lean concrete layer	Lean concrete layer	
Waterproof layer	Waterproof layer	Waterproof layer	Waterproof layer	Waterproof layer	
Pipe of waterproof system	Pipe of waterproof system	Pipe of waterproof system	Pipe of waterproof system	Pipe of waterproof system	
Water pipe	Water pipe	Water pipe	Water pipe	Water pipe	
Bentonite ribbon	Bentonite ribbon	Bentonite ribbon	Bentonite ribbon	Bentonite ribbon	
	Bolt Swellex	Steel rib	Steel rib	Self-drilling steel rib	
			Steel pipe	Steel pipe	
			Fiberglass pipe	Fiberglass pipe	
			Drainage pipe	Drainage pipe	

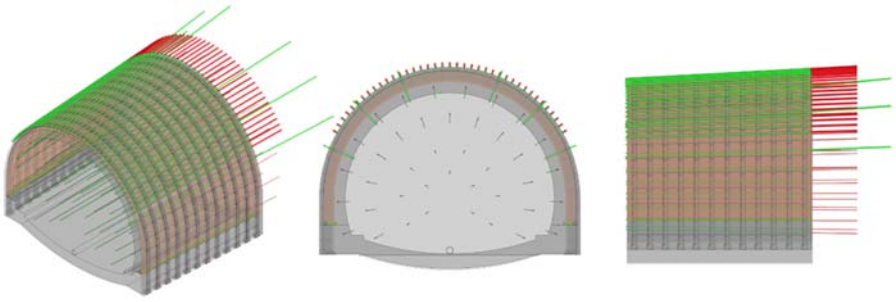


Figure 2. Section Type B1 of Paniga tunnel. Perspective, frontal and lateral view from parametric model

Consequently, it is possible to create the entire extension of the tunnel composing these primary sections. In figure 2 the section type B1 is represented in three different types of views. The section type is composed by different elements, which belong to the infrastructure object library created for this project.

2.3. Information exchange

Another important benefit from BIM methodology is the possibility to reuse information generated during the modelling process, avoiding data duplication. BIM model interoperability can be exploited during design phase to perform specific analysis, such as geotechnical, structural, etc. In this research, the interoperability process from Revit to two different FEM software is tested, in order to determine benefits and criticality of the process.

In particular, tested software are RS3, by Rocscience and MIDAS GTS NX, by MIDAS IT. Firstly, information exchanged is represented only by geometry data, because any other type of data can't be shared with FEM software due to proprietary information format problems. So the tested format was DXF (Data eXchange Format). In both cases the interoperability flow involved an intermediate step, using AutoCAD by Autodesk, in order to facilitate the communication (figure 3).

With the RS3 software, after exporting DXF from Revit, it is necessary to edit this file in AutoCAD, renaming lines and polylines with a specific Layer Name (e.g. Excavation, Material, ect.) and a specific AutoCAD Entity Type (e.g. closed line or polyline, line or polyline, etc.). After that, it is possible to import the modified file in RS3 by using the DXF Import Dialog. With MIDAS GYS NX software, after exporting DXF file from Revit, it is only necessary to explode all the polylines in AutoCAD, in order to correctly import the geometries.

3. Numerical analysis

Once defined the right interoperability path, starting from BIM model it was possible pass to numerical analysis. The ground-structure interaction was delivered with the use of three-dimensional finite element software RS^3, produced by Rocscience of Toronto.

In the preliminary phase was necessary to define the boundary conditions and the initial conditions in terms of stress state, to define the material behaviour and the failure criterion of rock mass and to define the applied support. Thereafter it has to be set the excavation sequence and supports installation sequence so to simulate the real construction phases and, as a last stage, the model has to be meshed.

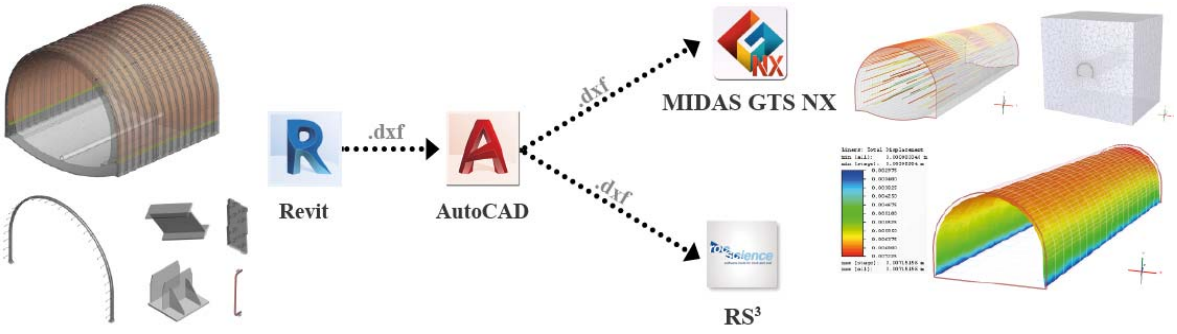


Figure 3. Interoperability workflow for FEM analysis

Finally, the computation is run, which allows to evaluate the results. In order to represent every possibility, different analyses were run:

Model 1: the excavation of a single slice with 60 m of depth was considered, the A2 section type was applied and the same conditions chosen for the two-dimensional analysis previously described were set

Model 2: it is defined as the mode 1 but, in addition the detachment of a rock mass wedge on the aged primary lining is modelled

Mode 3: the excavation of single slice with 60 m of depth was considered and the B1 section type was applied. The studied geological section is along the Selva Piana tunnel, at the km 14+810, in the GM-cataclastic zone unit, with an overburden of 145 m.

Table 2. The pertinent data for the three model.
General data, excavation data, and rock mass data for Model 1, 2 and 3

		Model 1	**Model 2**	**Model 4**
Tunnel	-	Selva Piana	Selva Piana	Selva Piana
Geomechanical unit	-	GM	GM	GM-cataclastic zone
Section type	-	A2 (cylindrical)	A2 (cylindrical)	B1 (truncated cone)
Chainage	x [km]	13+390 ÷13+450	13+390 ÷13+450	14+780 ÷14+840
Eq.tunnel radius	R [m]	6,30	6,30	7,00
Overburden	Z [m]	195	195	145
Unit weight	γ [kN/m^3]	27	27	27
Cohesion	c [MPa]	0.8	0.8	0.8
Friction angle	φ [°]	46	46	46
Young modulus	E [MPa]	7000	7000	7000
Poisson ratio	ν [–]	0.25	0.25	0.25

3.1. Boundary condition and initial conditions

The boundaries conditions and initial condition are the same for the three models. In order to not influence the tunnel behaviour, the external boundaries was placed at a fixed distance. Furthermore, as is visible in the figure 4, the constrains are in longitudinal direction for the two faces perpendicular to Z direction and for the other face to XYZ. In according to the assumption of deep circular tunnel, the field stress is assumed constant with depth and it corresponds with the lithostatic field stress, assuming a coefficient of earth pressure at rest K0 equal to 1. Of course its value varies with the value of the overburden that is different for the Model 3. Finally, as is visible the mesh of numerical model is composed by 10 linked tetrahedron elements.

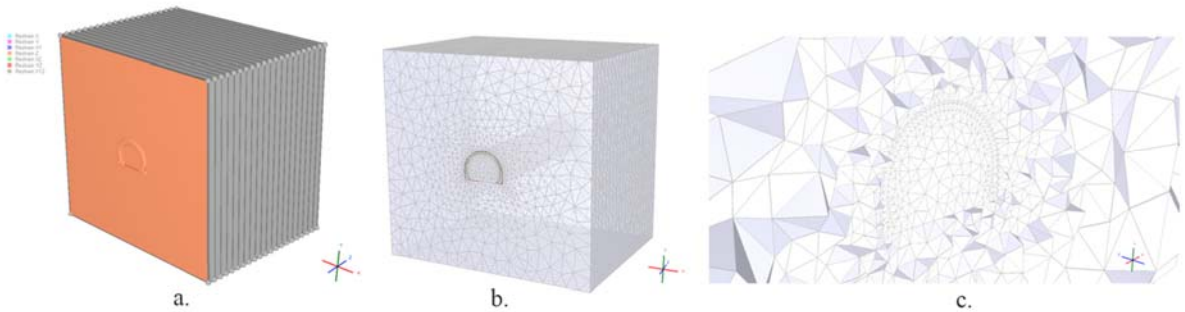


Figure 4. Restrains of numerical model (a). Meshed numerical model (b). Detail of mesh (c)

3.2. Simulation of executive phases

The software RS3 allows to define the sequence of the executive phase with the sequence designer. The relevant phases for the geotechnical and structural analyses modelled are: i) the excavation sequenced in 3 m sections followed by the installation of fresh primary lining; ii) the aging of primary lining with 6 m of delay; iii) the installation of final lining sequenced in 3 m section ad material backfill with 30 m of delay; iv) the complete removal of all the primary linings and the decrement of 10% for Young modulus of rock mass.

In the Model 2 (figure 5) the detach of rock mass wedge is simulated applying a triangular distributed load on the top-right side of mature primary lining, with a pyramid trend of 6 m in longitudinal direction, reaching the maximum value of 0,3 MN/m2.

The Model 3 (figure5) present the same phase but it's more complicate for the presence of 455 element taking into account the steel pipes, the fiberglass and primary lining and also for the excavation length of 1 m that involve much more calculation steps.

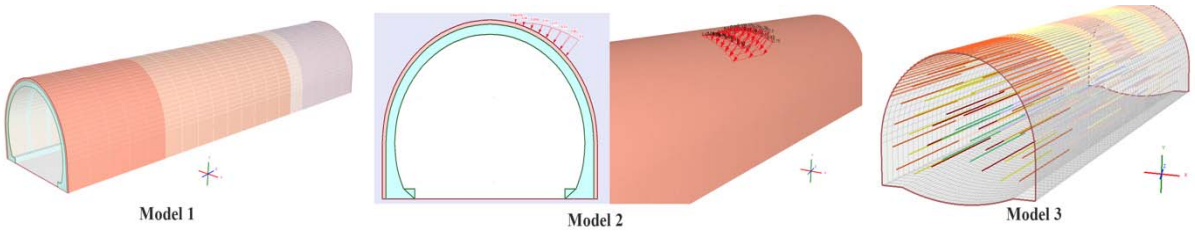


Figure 5. Models sequences phases, detachment of a rock mass 'wedge and steel pipes and fiberglass pipes

In particular for Model 3 it was necessary adopting some assumption, due to limitation of RS3 software that didn't allow to model the truncated con section that was modelled as a cylindrical section assuming its medium dimensions. As a consequence, the steel pipes placed on the tunnel crown have null inclination. Therefore, to avoid any contact between a set and the following one for their overlapping length, the steel pipes were misaligned on the plane perpendicular to the tunnel longitudinal direction. Also, the fiberglass pipes were modelled with null inclination and the consecutive sets were misaligned on the plane perpendicular to the tunnel direction. Often to represent the reality with a model is necessary to reach a compromise trying to model what is more useful for calculation purposes and that therefore allows one to obtain reliable results despite the assumptions.

4. Results

One of the most important results of this paper is the creation of a parametric BIM model car reach LOD 4 useful both for the structural analysis phase and the design phase.

Thanks to the interoperability process, it was possible exchange information from BIM model to FEM software, avoiding the replication of the structural model and the errors. Unfortunately, at the moment this process does not allow the bi-directionality and some information like material or other about soil characteristics are not shared.

Nevertheless, summarizing the numerical analysis results (table 3 and 4), obtained by the analyses of different models, was highlighted that the displacement (figure 6) on the contour excavation are not bigger than the value of 14 mm, values reached on the middle of basement for the phase 6, confirming the stable behaviour of the rock mass. It is possible to notice the almost null variation in terms of

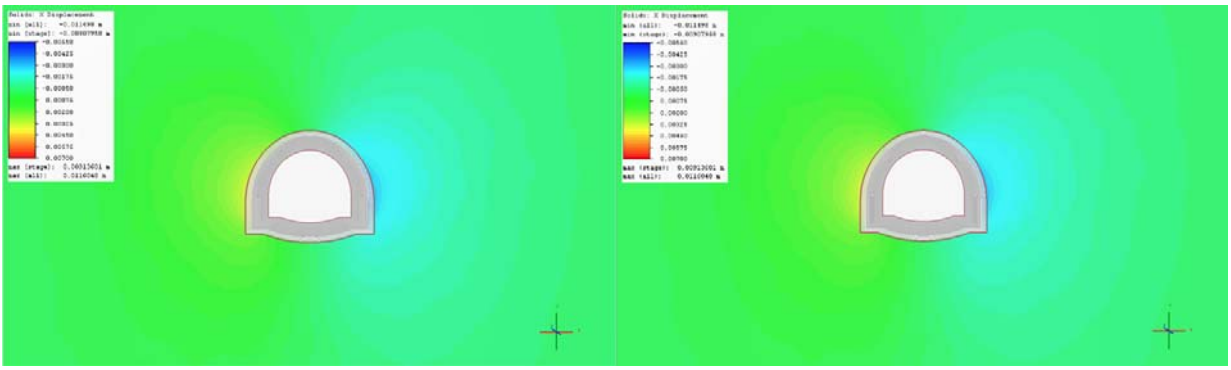


Figure 6. Examples of horizontal and vertical displacement

horizontal and vertical displacements between the phases 3 and 4 whereas a bigger variation is occurred between the phases 4 and 6. Unfortunately, for section B1 is not possible to make a comparison between the convergence values measured in the field because at date they are not yet available. The stresses acting on primary lining reach their maximum value on the spring lines and side walls, in particular the Axial force shows some singularity on the start and end liners (figure 7) whereas the Moment shows an increment on side walls for all the length of the model (figure 8). The Axial Force and the Moment for mature shotcrete, on average, have a doubled value respect to the value for fresh shotcrete. In terms of displacements, the primary lining reach their maximum value (10 mm) on the crown decreasing gradually towards the spring lines. The stresses acting on the steel pipe umbrella are negligible; the Axial Force is null, the maximum Shear Force values is 0,006 MN and the maximum Moment is 0,0006 MNm. This is due to the high geomechanical properties of the modelled rock mass so, consequently, the rock mass transfers an insignificant load to the steel pipes. Indeed, the rock mass would have a stable behavior even if the steel pipe umbrella and the pre-support at the front are not installed.

Table 3. Maximum horizontal and vertical displacement for different stages

Phase	Description	Max displacement [mm]	
		Horizontal, u_h	Vertical, u_h
3	Sequenced excavation	5,5	3,6
4	Primary lining installation	5,6	5
6	Final linin installation	9,4	13,3

Table 4. Maximum stressed acting on primary lining for different stages

Phase	Description	Max stress on primary lining		
		N [MN/m]	T [MN]	M [MN]
3	Primary lining installation	0,57	0,013	0,004
5	Final lining installation	1,13	0,017	0,007

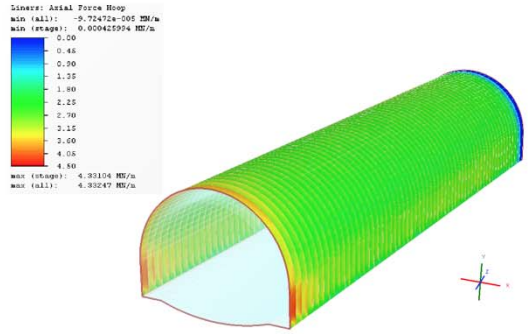


Figure 7. Axial force acting on primary lining for whole model

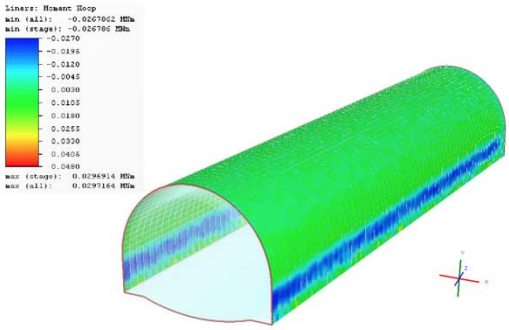
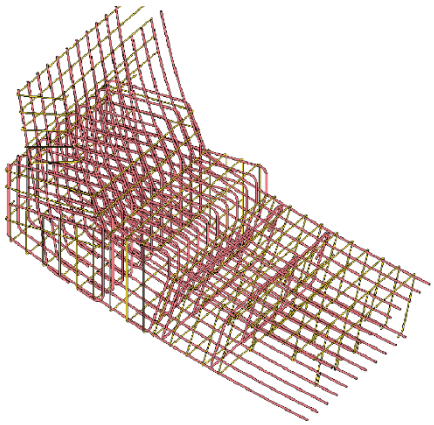


Figure 8. Moment acting on primary lining for whole model

At the same time, in order to obtain a parametric BIM mode useful for the design phase, it was crucial to realize a library of components. This phase requires a relevant effort in terms of expertise and time but it is essential to provide a BIM parametric model from which it is possible obtain a large amount of data such as steel rib, rebar quantities, concrete quantities, material schedules and etc. (figure 9). In this regard, it is interesting highlight how the parametric model determines an overall number of rebar element equal to 7711 and an overall weight of 36821 Kg. Performing the same calculation with traditional approach, based on the calculation analysis from executive design draft, the total weight of rebar is equal to 28900 kg. Comparing these results, it was possible to notice an underestimation of 21%, which means that using 3D parametric model it is possible to be more precisely.

Furthermore, the creation of a LOD4 3D model it is useful during construction phase, for workmen when they have to assembly them.



<REBAR QUANTITY>

A	B	C	D	E	F	G
Position	Quantity	Diameter (mm)	Lenght (cm)	Comments	Volume (cmc)	Weight (kg)
01	23	24	19775	5 ϕ 24/m	89458.367	702.25
01a	23	24	19775	5 ϕ 24/m	89458.367	702.25
02	23	24	12585	5 ϕ 24/m	56840.759	446.20
02a	23	24	12585	5 ϕ 24/m	56840.759	446.20
03_1	5	14	467	ϕ 14/ 40-40	718.676	5.64
03_2	6	14	560	ϕ 14/ 40-40	862.411	6.77
03_3	5	14	467	ϕ 14/ 40-40	718.676	5.64
03_4	6	14	560	ϕ 14/ 40-40	862.411	6.77
03_5	5	14	467	ϕ 14/ 40-40	718.676	5.64
03_6	6	14	560	ϕ 14/ 40-40	862.411	6.77
03_7	5	14	467	ϕ 14/ 40-40	718.676	5.64
03_8	6	14	560	ϕ 14/ 40-40	862.411	6.77
03_9	5	14	467	ϕ 14/ 40-40	718.676	5.64
03_10	6	14	560	ϕ 14/ 40-40	862.411	6.77
03_11	5	14	467	ϕ 14/ 40-40	718.676	5.64
03_12	6	14	560	ϕ 14/ 40-40	862.411	6.77
03_13	5	14	467	ϕ 14/ 40-40	718.676	5.64
03_14	6	14	560	ϕ 14/ 40-40	862.411	6.77

Figure 9. Example of rebar detail and extract of rebar quantity schedule with parameters such position, quantity, diameter, length, volume and weight.

5. Conclusions and future works

In conclusion, the research has obtained positive results for the setting up of the methodology and especially for the design phase. In fact, the development of BIM model to design the infrastructure, improves and optimizes the design process taking advantages from the information achieved in the BIM database for specific analysis, such as the geotechnical ones, avoiding data duplication and errors related to that.

The BIM methodology permits to qualify the process, also in terms of better control of project elements, such as reinforcing bars, rebars, etc., in the meaning of quantity take off and related economic values. Thus, the future works will involve the studies on the interoperability between GIS and BIM, in order to simplify data sharing among different disciplines, in particular regarding the implementation of a GIS database of geological information of the soil interoperable with the BIM environment, in order to facilitate data exchange for specific analysis. Another interest of further investigations will be the creation of libraries dedicated to infrastructure design.

Acknowledgments
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