Geotechnical engineering and process of digitalization – BIM modelling

Ivan Vaniček 1*, Jan Pruška 2, Daniel Jirásko 2, and Martin Vaniček 2

1Czech Technical University in Prague, 1580/3, Jugoslávských Partyzánů, 16000, Prague, Czech Republic
2Geosyntetika Ltd., 1798/5, Myslivečkova Prague, 16200, Czech Republic

Abstract. The digitization process has been going very fast lately as well BIM modelling, as both are strongly connected. The paper briefly evaluates this process from different levels, with the main focus on the conceptual level. The 3D geotechnical model of the ground comes to the fore, as this ground plays an important role also in the process of the BIM because practically all building structures are situated on this ground. Since the EN 1997 Geotechnical design also uses geotechnical and computational models, their connection with the BIM process is very useful and brings new possibilities. Especially from the point of view of connecting the design of the superstructure with substructure and ground and thus the presentation of the result in BIM model of the whole building. BIM models are presented not only for foundation structures, but also for earth structures and their advantages are shown, especially from the view of the decision-making process, as in the design and implementation phase so in throughout the service life of the building.

1 Introduction

The digitization process in the construction industry is associated with the term Construction 4.0 and is closely related to the term Industry 4.0. BIM (Building Information Modelling) plays an important role in this process both for the construction optimization process and for communication in construction.

Simply said, it is the application of similar processes, which were first initiated in the industry, where any product is composed of components that are broken down, up to the "smallest screw". However, this screw is not only a smallest part of the product, but it must be manufactured, precisely marked, stored, be in a precise place at a precisely defined time, etc. In the construction industry, this process is more demanding, especially due to the greater complexity of large structures. But the problem of higher claims is mostly connected with ground, with soil-rock environment, which is a natural environment with significant variability, inhomogeneity, the properties of which must first be determined. This is a great difference compared to the industrial elements, which are products created by human activity with predefined properties. But similarly to industry, in the case of construction it is not just a structural model in 3D. We can talk also about other dimensions,
4D, 5D, 6D…, what is after that a model (digital representation) enriched about construction process development as a function of time, cost, object management, etc. Therefore, you can also find the meaning of the abbreviation BIM as „Building Information management“. The BIM process thus offers great opportunities in the digitization process and its role will be shown for the field of geotechnical engineering.

2 Superstructure, substructure and ground

It is often used to say that the safety of a civil engineering project, a building, strongly depends on the way it is founded, how much it is based on "good" foundations. High-quality foundation structures (substructure) thus ensure the safe foundation of buildings, as practically all of them interact with the ground. But the saying needs to be completed. Foundation structures can ensure the safety of the superstructure only in the case that they are well adapted to the properties of this ground. Therefore, the basic BIM model, the 3D model of the proposed structure must also be based on the 3D model of the rock environment / foundation soil / subsoil, Figure 1.

The subsoil model must include at least the area of the subsoil which is affected by the structure and is of fundamental importance for the limit states of failure. This fact can be summed up by the already commonly accepted statement “A part of the construction is also a part of the subsoil, which is affected by the construction, resp. its properties affect the construction”. Therefore, any BIM model of a construction must start with a 3D model of the subsoil / rock environment / foundation soil, and this is one of the basic tasks of the field of geotechnical engineering. The second no less important task is also 3D models of basic geotechnical structures. When we talk for foundation structures about construction on ground; for earth structures about construction with ground, as soil, rock are the basic building materials; and for underground structures about construction in ground, inside of the rock environment.

Fig. 1. Mutual interaction between superstructure – foundations (substructure) and affected ground.

3 Basic elements of the BIM complex model

Currently, the attention to the BIM process has several levels, each of which is very important in itself for the overall significance.
The conceptual level can be seen in one of the basic definitions of the BIM process. BIM is a shared source of knowledge, information about the device, creating a reliable basis for decision-making process during its life cycle defined from the first concept to demolition. In other words - BIM is a process for optimizing the preparation, design, implementation and operation of building structures. Some ideas about the benefits of BIM include - BIM is about change of processes, thinking, work habits, respectively. "Contribute to greater efficiency in construction projects by improving collaboration, sharing information and cultivating relationships. Benefits of this conceptual level for the geotechnical engineering create the main content of this article.

Level of classification of building elements - from building units / entities to basic elements. The CCI Classification System - ISO 12006-2: 2015 is used for this purpose. The English version of the classification system is now being translated into different languages, in our case to the Czech, which is not an easy process, as in English often an expression can have a large number of interpretations. For example, for the English term from geotechnics - ground - you can find up to 60 different terms in Czech, for example rock environment, foundation soil or subsoil.

The basic division is based on the division of building units – entities, which are divided into units for human needs and activities, for technical objects and infrastructures with the addition of less frequent building units, such as "landscape" or "monument". It is obvious that in all cases the field of geotechnics fulfills their basis, it is an integral part of them. The similar division is from the point of view of the built space, when again it is primarily a space for human dwellings or spaces used by people for their activities, such as leisure and trade.

From a design point of view, the division according to the functionality of the system is more important, where the basis consists of:

- Ground system - a spatial system that delimits the building unit downwards
- Wall system - a spatial system that creates and separates space in the vertical direction
- Slab system - a spatial system that creates and separates space in the horizontal direction
- Roof system - a spatial system that terminates the structure upwards.

This is a clear determination of vertical, horizontal and bounded structural elements as ground system and roof system. Ground system is going down and includes rock environment and geotechnical structures, as foundation and underground structures and cuts of earth structures of transport engineering. The list continues with installation systems (gas, air, water, sewage and waste collection, etc.), with an important role here being played by the plumbing system, which protects the building against danger and damage, with a clear definition of the fire protection system.

This list thus corresponds to 4 basic professional specializations, which are today recognized as most responsible for the safety of buildings:

- Statics and dynamics (structural analysis) + Geotechnics (geotechnical engineering), which together ensure the mechanical resistance and stability of the building
- HVAC (heating, ventilation and air conditioning) - ensures optimal well-being, optimal use of space and safety of persons using the premises - especially from the point of view of health of persons using these spaces
- Fire safety - fire protection.

Therefore, for these 4 basic professional specializations, official experts are appointed - "Public appointed official Experts", who are to guarantee the fulfillment of these requirements. The importance of the first two will be reflected in the second generation of Eurocodes - common European standards for the design of building structures, when the basic standard - Eurocode 0 will be renamed as "Basis of Structural and Geotechnical Design" (prEN1990: 2018).
The development of the classification system is now ongoing, and the possibility of progressing from the most complex to the most basic can be shown for underground structures. The first stage of division can be into underground structures linear (having a transport character) or underground structures three-dimensional, e.g. for gas storage, storage of radioactive waste, sports grounds – as hockey hall for the Winter Olympics 1994 in Norway, etc. The second possible stage of division for linear underground structures can be according to the construction technology – by tunneling or by excavation in open pit; and so, it is possible to continue up to the details in the composition and specification of the tunnel lining.

Finally, the third level is connected with IT. Here it is clear that it is necessary to create a so-called data standard, which specifies the rules of data creation for BIM. Such data standard can be used by all partners in the preparatory process, as well as during the implementation and operational processes. Currently, the data standard is based on the IFC open data format - ISO 16739:2013, which specifies a conceptual data schema and an exchange file format for Building Information Model (BIM) data. It plays a major role in the creation and subsequent utilization of the Coordination Model of the building, which is composed of individual building sets, operational files or engineering structures. It is used for mutual coordination of partial models, for collision detection, for displaying the whole construction, for displaying individual stages of construction, creating total sections, etc. Simply saying, the coordination model is a basic separate set that serves partial models. Summarizing this section, it is clear that the good cooperation between the above three basic levels is needed. Only after that final successful result can be achieved. Unfortunately, the scope is so wide that for a novice who is to get acquainted with the whole BIM process, it is very demanding and in the first phase he has to find a certain balance between these levels.

4 Geotechnical models

The design of geotechnical structures is governed by Eurocode 7 Design of geotechnical structures (EN 1997). Including also demands on geotechnical investigation to obtain input data of the geotechnical parameters for geotechnical design, and together with them to be able to determine also the geotechnical actions on structures - loading from soil, rock and groundwater. The design principle, similar to other structures (concrete, reinforced concrete, steel, masonry, timber), is based on the verification of limit states (ultimate and serviceability) with the help of partial factors (for material, resistance, action), when it must be demonstrated that for any design situation these limit states are not exceeded. The precision and depth of verification is governed by the risk associated with the structure. Broadly speaking, the care devoted to the geotechnical investigation and design should correspond to the risk with which the structure failure is connected. For geotechnical structures, this risk is associated with the Geotechnical category. Therefore, the determination of the Geotechnical Category (GC) is appropriate already in the first stages of the design and investigation, in order to be able to follow it.

The actual design and implementation (construction) of the geotechnical structure has the following phases, Vaníček, Jirásko & Vaníček [1]:

- Geotechnical model of rock environment (Ground model);
- Geotechnical design model;
- Calculation model;
- Geotechnical structure execution, together with monitoring and control.

The Geotechnical model of the rock environment (Ground model) is the result of the Geotechnical Investigation Report, when in principle it consists of two basic parts:
a) Geological model of the rock environment, which divides the subsoil into lithological layers, quasi-homogeneous layers with similar geotechnical properties.

b) Results of all performed tests, both laboratory on samples taken and within field survey tests.

5 Geotechnical Model

The Geotechnical Model is gradually being refined when its two basic phases are the Preliminary Geotechnical Investigation (for the documentation for planning inquiry) and the Design/Detailed Geotechnical Investigation (for the documentation required for the building permit). A similar specification applies to test types. Index properties (state, physical, and chemical properties) are usually sufficient for the first phase (when their results for each specified lithological layer/geotechnical unit form a clear set). For the second phase, tests of mechanical and physical properties are already required in accordance with the Geotechnical Category. The 3D geotechnical model for the needs of the BIM model thus has 2 basic levels. The discussion of the construction process participants on the first one significantly helps to define the requirements for the geotechnical investigation of the second, design/detailed investigation phase.

During the geotechnical structure execution, after uncovering the footing bottom, walls of cuts, tunnel excavation face, etc. - the results of observations are described in the Confirmatory Investigation Report. The results are confronted with the results of previous investigation phases including with selection of representative values specified by designer and used in the calculation model. This corrected model of the ground is part of the documentation for real structure performance and is used for all life time structure expectation. Not only for the structure maintenance but also when new situations arise such as interaction with new construction, interaction with natural hazards or accidents etc.

6 Geotechnical Design Model

The Geotechnical Design Model contains not only specification of individual lithological layers/geotechnical units, but also representative / characteristic values of geotechnical parameters for each layer, which are then used in computational models. These representative values are selected by the designer from the set of results of the laboratory and field tests, as cautious estimate of values affecting limit states for which they are used. In the case of confirmatory investigation report for significant structures the representative values can be compared with results from this last step of geotechnical investigation, how much they were too conservative or, on the contrary, too optimistic.

7 Calculation Model

The Calculation Model is in principle based on the application of analytical or numerical methods. Today, the percentage of the use of numerical methods (mostly FEM) is increasing and in many cases, especially in situations where it is more appropriate to use a spatial solution in 3D than a planar solution in 2D.

8 Summary

In summary, in this section, it can be stated that the requirements of the Eurocode for procedures for the application of individual models overlap with the requirements for the BIM model. Therefore, the transition to it is smooth and non-violent, moreover with the
potential for significant use. The final note concerns the gradual interconnection of calculation models of the ground and foundation structures with computational models of the superstructure. Until now, the solution has often been carried out separately. Foundation structures were design with the help of actions from superstructure. On the contrary the superstructure was often calculated without any detailed knowledge about the ground. This ground was substituted only by some springs. It is not in agreement with demands of Eurocode, which especially for structures with higher risk, obligatorily requires the most accurate assessment of the ground properties. Gradually, there are solutions, sometimes referred to as "soil × structure interaction" where FEM can solve all parts at once. This requires higher demands on computer technology, but at present it is no longer such a limitation, Ulitsky & Lisyuk [2], Figure 2. This confirms the initial assumption shown in Figure 1 that the subsoil together with the foundations is part of the whole construction.

9 Importance of gradual creation of BIM model in geotechnical engineering

As already mentioned, BIM is a shared source of knowledge about equipment information, creating a reliable basis for decision-making during its life cycle defined from the first concept to demolition. Therefore, it is necessary to create the BIM model from the very beginning, for important constructions already for the investment project (idea). The first subsoil model can be appreciated in the initial phase of the investigation (desk study), which is based on archive and map data, where the basis consists of geological, engineering-geological and hydrogeological maps. Today, namely in the Czech Republic, there is a set of so-called geo-environmental maps, where there are up to 16 map sheets for a selected area, while in addition to the three maps already mentioned they inform about protected areas, sources of raw materials, important sources of drinking water, etc. We have
another important source of information obtained so far. The Geofond archive, stores data on previously performed ground investigations, including the location of survey points. The similar is valid for other descriptions obtained from various excavations, excavated wells, boreholes, field surveys which are sometimes supplemented with results of laboratory tests together with information on groundwater. When collecting documents for the investment project (idea), a personal on-site inspection and evaluation of the completed constructions in the vicinity of the newly planned one is also suitable. The first subsoil model is thus based on the spatial model of the surface of the territory, which is now freely available for use, and its extension by the subsoil using knowledge gained from the desk study. This initial model has a high informative value for the choice of alternatives, such as route management, or vice versa from the point of view of the EIA process, which is required in these cases. Today, two issues are being discussed in the geotechnical community. The first relates to the processing of data stored so far in the archives of the Geofond into a data standard suitable for fast (but critical) use (insertion) into the BIM model. The second relates to the free use of this data, as in the case of the spatial terrain model.

The report on the preliminary geotechnical investigation should, in addition to the already mentioned geological model together with the verification of the location of individual lithological layers (at least using descriptive, index properties), also contain a statement on the expected impact of the proposed structure on the rock ground (as is e.g. a process of EIA) and the like a statement on the expected response of this ground to the proposed construction. All this makes it easier for the designer to define the Geotechnical category and at the same time accept the principles of sustainable construction in his documentation for the zoning decision. For example, for earth structures of transport infrastructures, the principles of sustainable construction are associated with energy savings, greenfield savings, natural material savings, Vaníček & Vaníček [3]. The investor also plays a big role here, to what extent he will consider the principles of sustainable construction when choosing the most suitable documentation. For example, how he will appreciate the land (greenfield) savings, not only due to the necessity and complexity of its excavation, but also its price. Simply saying, steeper slopes (e.g. by reinforcing them) can save this land and also reduce the energy intensity of soil relocation. The application of by-products, including large-volume waste (e.g. fly ash, excavated material in the construction of underground spaces in the city, construction and demolition waste) can significantly reduce the demand for natural soils and rocks, and thus change the classically considered balance between the volume of cuts and embankments.

What is very important, however, is the ability to use the spatial 3D model to decide on the need for additional investigation points to cover the entire subsoil area affected by the superstructure, their frequency at major changes in the geological model, and to decide in which direction the next step of investigation should be directed. This naturally also applies to methods for more detailed verification of the groundwater level, its fluctuations, including the measurement of pore pressures using piezometers. The result is finding the optimum of the claim for the next phase of geotechnical investigation needed for the limit states verification in the calculation model, while respecting the risk to which the structure is associated - the Geotechnical category.

10 Position of geotechnical engineering in relation to the Coordination Model

For most buildings and civil engineering works with a clear construction system, this construction system forms the basis of the BIM model - the Coordination Model. The foundation structures with their model together with the subsoil model form one of the individual parametric elements of this coordination model. Both in the case of buildings or
civil engineering works, for example foundation of bridges. Such a bond between coordination (basic) model and individual parametric element is shown in Figure 3.a.

In contrast, Figure 3.b shows the case when the geotechnical structure together with the rock environment/ground forms the basis of the BIM model and other individual elements or parts of the structure are connected to it.

![Figure 3](image)

Fig. 3. The different position of a geotechnical BIM model. a) Geotechnical structure creates an individual parametric element around basic (coordination) BIM model. B) GS creates a basic BIM Model. (according to Vaníček, Jirásko & Vaníček [4].)

Examples are underground structures, such as the metro. A similar model can be applied to earth structures. In the first phase of the earth structures for transport engineering, the road specialist plays a decisive preparatory role (capacity, directional and height conditions, etc.), but the building element, which is the main part of the BIM model not only in the design and implementation phase but also operational ones, it is an earth structure. A similar analogy can be given for earth structures of hydro engineering such as earth or rockfill dams, small dams, dikes. Also, here in the first phase of the design are decisive hydrotechnical calculations (transformation of flood waves, overflow capacity, discharges), but the actual construction - the dam together with the subsoil is part of this earth structure and can create the basic BIM model. Therefore, it is important that more specialists are required in the construction documentation, but they must work very well together.

In connection with this, the question arises as to the extent to which BIM models should be used in transport structures, such as motorways, where earth structures, bridge structures and underground structures are the basis. It is possible to imagine an elementary model for the entire section of the motorway, but only for fundamental parameters. For more detailed parameters, then at least the division into the above three units. More detailed model of individual parts of the motorway can help very well during any accident within the motorway operational phase. Such accident can be caused by a truck carrying a dangerous chemical substance. BIM model can help very quickly to locate place of accident and determine the nature of the embankment and subsoil there, information needed for the evaluation of contaminant spreading and what remediation procedure should be chosen.
11 Examples of combined 3D models for geotechnical structures and ground

Figure 4 shows an example of the 3D model of the foundation structure consisting of a group of piles when the construction pit is protected by anchored vertical wall. Geotechnical model is present as well and this combined 3D BIM model is individual parametric element for whole BIM model of the proposed structure, according to Fig. 2.a. Investigation boreholes are marked here together with reference about borehole details – description of the geological profile, depth where field tests were performed or samples collected for lab testing, together with the results of these tests. Also, the lines of interface of the individual lithological layers/geotechnical units are drawn there. Similarly, each pile constructed has a reference to its performance, together with the test results, if any. The same applies to the elements of the vertical wall of the construction pit and the anchorage itself. The format in which the information specifying the individual data should be presented could be discussed.

Figure 5 gives an example of the earth structure for transport infrastructure consisting of a reinforced embankment together with a model of the ground, which contains vertical drains to speed up its consolidation. Detailed references are again not only for investigation points, as in the previous case, but also for the compacted embankment itself with marked inspection points and compaction quality test results, with references to the applied reinforcing geosynthetics, resp. on vertical drains. The spatial display serves to check the range of geotechnical investigation (frequency and depth) and the valuation of individual lithological layers. At the same time also provides information on the materials used for the embankment and their specifications, including the results of control tests, proof of a well-executed earth structure.

It is clear from the list that these models provide sufficient support for the general importance of the BIM process; basis for the decision-making process, including sufficient space for improved cooperation, information sharing and cultivation of relationships leading to higher efficiency of construction projects.

Fig. 4. Combined geotechnical BIM model of the ground and foundation structure.
12 Preparation of the branch of geotechnical engineering for the BIM process

Acceptance of BIM model in the branch of HVAC (heating, ventilation and air conditioning) is very good, also for the phase of utilization – for maintenance and reconstruction, due to shorter life time expectancy than for the structure itself. However, it can be reasonably expected that the main advantages are there for large civil engineering projects, connected with high risk. Traffic constructions, water and environmental works fall very often into this high-risk group. Since the role of geotechnical engineering is extremely important for these civil engineering works, not only in terms of specifying the properties of the ground, but also in terms of elementary geotechnical structures - earth, underground and foundation structures, the BIM process must be given due attention. The advantage is the fact that Eurocode 7 (EN 1997) also pays high attention to individual models (especially geotechnical and calculation), so the transition is relatively smooth from a professional point of view. However, it requires higher specification hardware in order to run complex 3D software for both numerical analyses of combined soil structure interaction and their visualization in 3D BIM models.

13 Conclusion

It can be stated that the geotechnical community has understood the main benefits of the BIM process and is ready to fulfil its role. Therefore, various views of the whole process were described, including simple examples of possible presentation of BIM models. The role of the branch of geotechnical engineering was pointed out, which is irreplaceable, especially in the preparation of a combined 3D BIM model of the rock environment/ground with elementary geotechnical structures - foundation, earth and underground. At the same time, the importance of foundation structures, which mediate the interaction between the superstructure and the substructure, including the ground, was shown. The result of good interaction ensures the fundamental requirement for buildings and civil engineering works, to ensure mechanical resistance and stability. This cannot be met without solving also the ultimate and serviceability limit states of the ground in the manner specified in EN 1997. At the same time, the combined 3D BIM model of the ground and geotechnical structure
cultivates the relationships between the individual participants in the construction process and contributes to the greater efficiency of construction projects.

References


3. I. Vaníček, M. Vaníček, Earth structures in transport, water and environmental engineering (Springer, 2008)