Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0748

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Utilizing building information modelling for embankment settlement calculations

Utilisation du BIM, Building Information Modelling, pour les calculs de règlement de remblai

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ABSTRACT: The infraconstruction industry in Finland trends strongly towards BIM-based design, construction and maintenance. However, existing geotechnical computation software cannot use BIM –models directly as a source of calculation geometry. Therefore, as far as geotechnical design is concerned, BIM-based projects are in large part carried out with a traditional document-based design process, as majority of the design calculations are performed with hard copies of cross-sections.

In this paper a Matlab-code for a compression index -based settlement calculation engine was developed. The calculation engine uses the coordinate information from the BIM –model as a source of model geometry. Thus, instead of a cross-section, the calculation model for settlement calculations is generated three-dimensionally directly according to the BIM –model. However, only vertical stresses and deformations are considered in the calculation engine. The main output of the calculation engine is a heatmap of calculated settlements for a given x, y -coordinate range.

In addition, a Monte Carlo –simulation for settlement calculation was implemented in the calculation engine. When Monte Carlo –simulation is used in the engine, the soil parameters are given by statistical distributions. The calculation is then repeated several times by generating random parameters for each calculation according to given distributions. By using Monte Carlo –simulation, a distribution of calculated settlements is obtained. The distribution may then be further utilized to calculate propabilities of excessive overall or differential settlements.

RÉSUMÉ: L'industrie de l'infrastructure en Finlande est fortement orientée sur la conception, la construction et la maintenance basées sur le BIM. Toutefois, le logiciel de calcul géotechnique existant ne peut pas directement utiliser les modèles BIM comme source de géométrie de calcul. Par conséquent, en ce qui concerne la conception géotechnique, les projets basés sur le BIM sont en grande partie réalisés selon un processus de conception classique basé sur des documents, car la majorité des calculs de conception sont effectués avec des copies papier de coupes transversales.

Dans cet article, un code MATLAB pour un moteur de calcul basé sur un indice de compression a été développé. Le moteur de calcul utilise les coordonnées du modèle BIM comme source de géométrie du modèle. Ainsi, au lieu d'une coupe transversale, le modèle de calcul des calculs de règlement est généré en trois dimensions directement selon le modèle BIM. Toutefois, seules les contraintes et déformations verticales sont considérées dans le moteur de calcul. La sortie principale du moteur de calcul est une carte thermique de règlements calculés pour une certaine plage de coordonnées x, y.

En outre, une simulation Monte-Carlo pour le calcul du règlement a été mise en œuvre dans le moteur de calcul. Lorsque la simulation Monte Carlo est utilisée dans le moteur, les paramètres du sol sont fournis par des distributions statistiques. Le calcul est ensuite répété plusieurs fois en générant des paramètres aléatoires pour chaque calcul selon les distributions données. En utilisant la simulation Monte Carlo, on obtient une distribution de règlements calculé. La distribution peut ensuite être utilisée pour calculer la probabilité des règlements globaux ou différentiels excessifs.

Keywords: BIM; settlement calculation; Monte Carlo -simulation

1 INTRODUCTION

In current practice the analysis for settlement behaviour of an embankment on soft soil is typically performed with two-dimensional calculation models. Differential settlements along the length of the embankment are assessed by comparing calculated settlements of two or more cross-sections, or by calculating settlements using a longitudinal section of the embankment as a calculation model. Cross-sectional calculation models inherently contain a plane strain simplification, where the loading conditions and soil geometry are assumed to be constant perpendicular to the cross-section. However, in reality settlement problems are always three-dimensional.

Furthermore, in a settlement calculation model the subsoil is typically modeled by dividing the soil into layers and by giving each soil layer single values for deformation parameters. It is assumed that deformation parameters within a soil layer are spatially constant. However, research has shown that the variation of soft soil deformation parameters is substantial even within short distances (Akbas & Kulhawy 2010, Phoon & Kulhawy 1999, Löfman 2016).

Ignoring soil parameter variation and making the assumption of plane strain may lead to significant error in embankment settlement calculations. It might be possible to reduce this error by modelling soil parameters with statistical distributions and by modelling the embankment loading situation and soil geometry three-dimensionally according to a three-dimensional BIM-model. However, there is currently hardly any computational software available for this type of analysis.

Digitalization of the infrastructure construction industry requires updating of geotechnical design tools for achieving full benefits of BIM in geotechnical engineering. Majority of existing software used for geotechnical design consider only two-dimensional problems. Though three-dimensional computational software is available, they generally do not support the BIM data transfering format Inframodel commonly used in Finland or the international LandXML-format on which the Inframodel-format is based. Thus, the BIM-model cannot be directly used as a calculation model for geotechnical analysis. In addition, the results from the analysis cannot be viewed and examined using the BIM-model.

In order to tackle the problem of incompatibility of BIM-models with existing embankment settlement calculation software, this paper presents a prototype of a compression index method -based primary consolidation settlement calculation engine that uses the embankment and soil layer xml-surfaces from a BIM-model as input for 3D calculation model geometry. Additionally, for quantifying the possible error in settlement calculations, the possibility of a Monte Carlo -simulation by varying soil parameters is also included in the calculation engine.

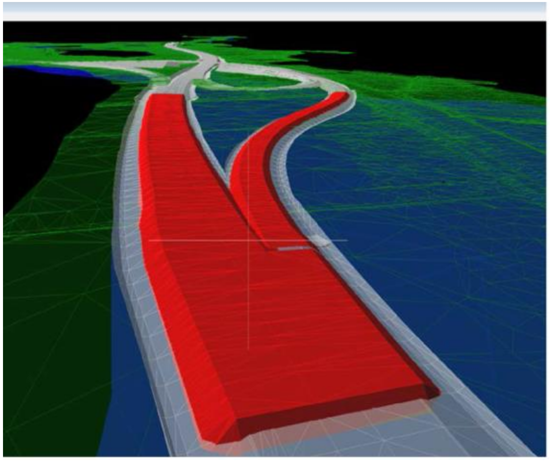


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Figure 1. Example of a BIM-model. Preloading embankment (red) and corresponding Inframodel data

2 BIM-MODEL AS INPUT FOR CALCULATIONS

2.1 Inframodel data format and triangulated surfaces

Currently in Finland, the design and construction of earth structures are carried out in an increasingly large part using BIM-models. A LandXML-based national Inframodel-format is used for information transfer between software and different parties of the project. The relevant information concerning settlement calculations included in the Inframodel format is presented in Table 1 (Liukas 2013).

The BIM settlement calculation engine presented in this paper uses the coordinate information from relevant triangulated surfaces (eg. excavation surface, embankment surface, soil layer and groundwater surfaces) from the BIM-model as input for calculation model geometry. The coordinate information and hence the geometry of the surfaces can be accessed using the xml-files of the surfaces. Figure 1 presents an example of a BIM-model visualization and corresponding Inframodel data of one of the surfaces.

Table 1. Information included in the Inframodel-format (Liukas 2013)

Subject	Contents
Model overview	- project name - identification - units - coordinate system
Existing soil and terrain	- existing ground points - subsoil layer points - triangulated surfaces
Highways, railways, streets	- course layers as breaklines and triangulated surfaces
Area planning	- shaped surfaces - landscaping - landfills
Soil improvement	- counter embankments - surgharge embankments - mass exchange - deep stabilization - lightweight fills

2.2 BIM-model accuracy

The accuracy of the BIM-model surfaces vary during the design process. In many cases, even in final construction phases the BIM-model contains information of varying resolution and accuracy. Figure 2 demonstrates the resolution of different surfaces of the BIM-model in Figure 1.

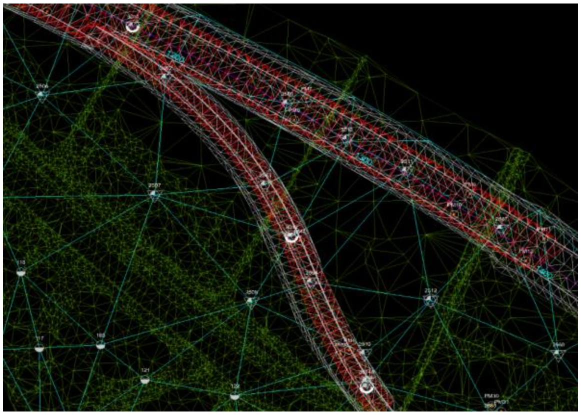

Figure 2. Triangulation of surfaces in Figure 1

From Figure 2, it can be seen that the existing ground, designed preloading and final road embankment surfaces are modeled with rather dense triangulation. However, the bottom surface of clay (cyan in Figure 2) is based on triangulation between soundings located at a maximum distance of 100 meters from each other. Sparse triangulation of clay layer surfaces may have a substantial effect on the accuracy of settlement calculations, as the thickness of clay layers is a crucial variable in calculations.

However, the BIM-model itself is not a direct reason for possible settlement calculation error due to model geometry inaccuracy. Rather, the accuracy of soil layers in the BIM-model is dependent on the quality and distances between soil investigations. Furthermore, using a BIM-model as input for settlement analysis does not remove engineering judgement from constructing the calculation model. The soil layer points and hence the layer surface shapes are always interpreted by a geotechnical engineer. In most cases, extra points are added into the soil layer surface in order to model the surface correctly according to a geotechnical interpretation.

3 BIM SETTLEMENT CALCULATION ENGINE

3.1 Calculation principles

3.1.1 User input

The BIM settlement calculation engine was programmed using Matlab. The calculation program forms a 3D-calculation model by reading the relevant surfaces as modified text files, which contain the three x, y, z -points of every triangle in the corresponding TIN-surface. In the prototype program version, it is possible to read 5 different surfaces to take into account in settlement calculations. These surfaces are the embankment top surface, existing ground, excavation surface, dry curst bottom layer (also regarded as groundwater surface), soft soil bottom surface and a possible top surface of embankment constructed of lightweight materials. A calculation model formed in Matlab using the BIM-model surfaces from Figures 1 and 2 is shown in Figure 3.

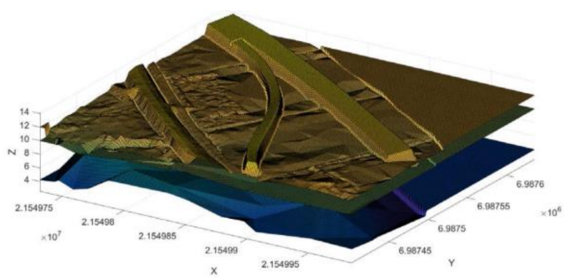

Figure 3. Matlab calculation model of BIM-model surfaces

In the main code, the calculation engine requires user input for embankment and subsoil layer unit weights and for the spacing of calculation points along each coordinate axle. The extent of area in the calculation is by default determined by the embankment surface file minimum and maximum x, y -coordinates, but it can be changed by the user. The user is also able to determine a cross-section location along the x-axle for examining the calculation model in a cross-sectional view. An example of a cross-sectional view of a calculation model is in Figure 4.

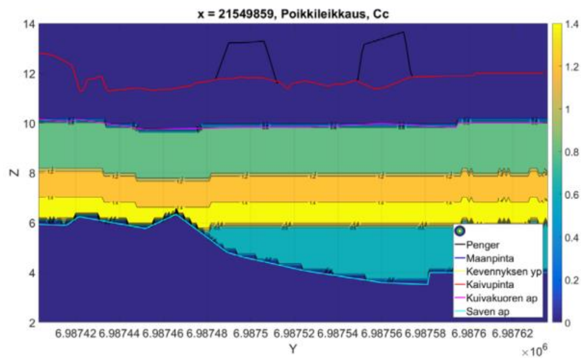

Figure 4. Cross-sectional view showing different surfaces and the compression index of soil in a calculation model (different scales for y and z)

Soil deformation parameter input is separated from the main code into individual functions whom the main code calls. Parameters are given by the user with these functions. Within the soil parameter functions, it is possible to divide the subsoil into more layers by determining different parameters for each layer.

Furthermore, there are also separate soil parameter functions used in Monte Carlo simulation. Monte Carlo parameter functions determine the means of parameter variation. The output in the main code from the parameter functions is 3D-arrays containing the values for each parameter in each calculation point for each simulation. Thus, in principle it is possible to vary the parameters with an arbitrary distribution and manner, as long as the parameter variation code is written inside the Monte Carlo soil parameter functions.

3.1.2 Calculations

At first, three-dimensional arrays are initialized to store calculation information. The elements in these arrays represent soil parameters and different calculated values in each calculation point of the model.

Although the calculation model is formed three-dimensionally according to the BIM-model, only vertical stresses and deformations are considered in calculations. Initial vertical stresses in the subsoil are calculated using the existing ground and soil layer surfaces in the BIM-model and the input of unit weights of soil.

The embankment load is modelled by discretizing the 3D embankment surface into vertical point loads acting on the ground surface. The stress in the subsoil due to a point load is assumed to obey the Boussinesq theory of point loading. The additional stress due to the whole embankment loading is then calculated with numerical integration over all point loads in each calculation point.

As the initial and additional stresses are now known and each point has deformation parameters, the strain of each point is calculated. The settlement of the embankment at each x, y -point is then calculated by summing the strains at points with the same x, y -coordinates multiplied by the distance between points in the z-direction. Finally, the settlements of each x, y -point are deducted from the original embankment surface z-coordinates and a text file of the same format as the original surface file read into the program is written.

3.1.3 Output

The text file of the settled embankment can be utilized to create a surface, which can be imported and reviewed in the BIM-model. Additionally, the calculation program produces comprehensive planar, cross-sectional and three-dimensional windows for examining calculation results. Calculation result examples are shown in Figures 5 and 6.

Presumably, the most important calculation result for evaluating the feasibility of the embankment without soil improvement is a heatmap of calculated settlements. An example heatmap is shown in Figure 7. By observing the heatmap, it is possible to easily recognize locations of too large overall or differential settlements. Individual values are also accessible by observing the arrays containing the calculation data of each point.

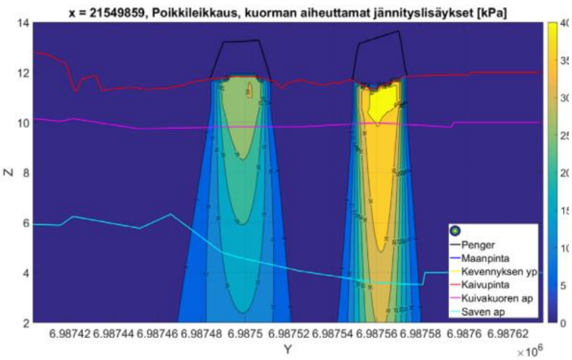

Figure 5. Cross-sectional view, additional stresses due to embankment loading (different scales for y and z)

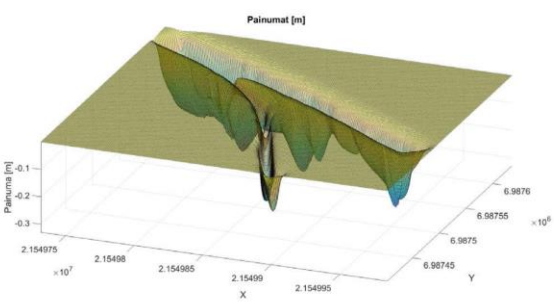

Figure 6. Calculated settlements in 3D, the user is able to zoom and rotate the view

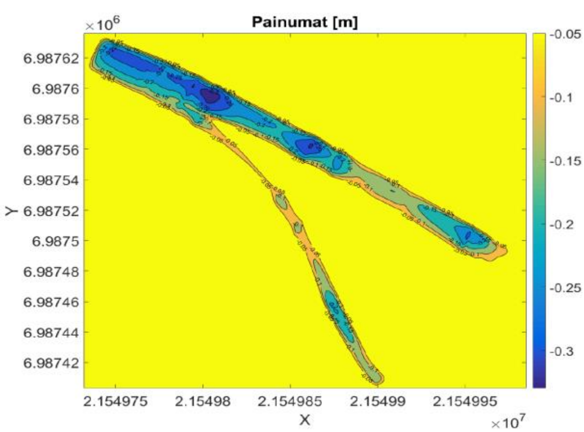

Figure 7. Heatmap of calculated settlements

3.2 Testing and validation

Computational validity of the BIM settlement calculation engine was verified using simple artificial surfaces as input for calculation geometry. The results were compared with the results of a corresponding cross-sectional calculation using existing and commonly used settlement calculation programs. Four cases were considered: embankent on top of existing ground with horizontal surfaces, embankment with excavation for course layers, slanted surfaces with a ditch in the existing ground and embankment with lightweight materials excavated and filled into the existing ground. All four cases showed that the BIM settlement calculation program yields settlements similar to existing 2D calculation software, when the geometry is constant and the embankment long enough so that plane strain assumption is accurate. Comparison of settlements calculated using the model in Figure 8 and with existing 2D software is shown in Figure 9.

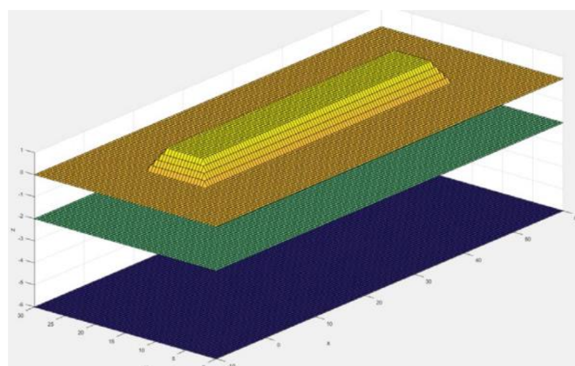

Figure 8. Calculation model for result comparison

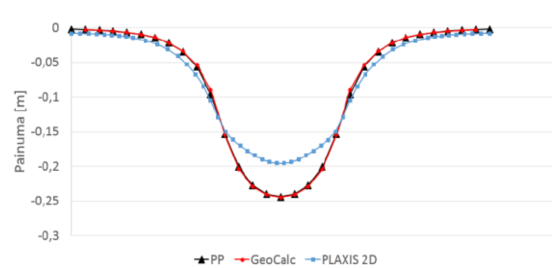

Figure 9. Calculated settlements in the middle of the embankment (PP = BIM settlement engine)

Furthermore, the engine was tested using real BIM-model surfaces. The settlements of the preloading embankments shown in Figure 1 were calculated and compared with cross-sectional calculation and also with measured settlements after 11 months of preloading. The settlements on site were measured using settlement plates located in pairs on the opposite shoulders of the embankment. Figure 10 shows the measured time-settlement diagrams and calculated primary consolidation settlements of the spots of settlement plates. A heatmap of calculated settlements is presented in Figure 7.

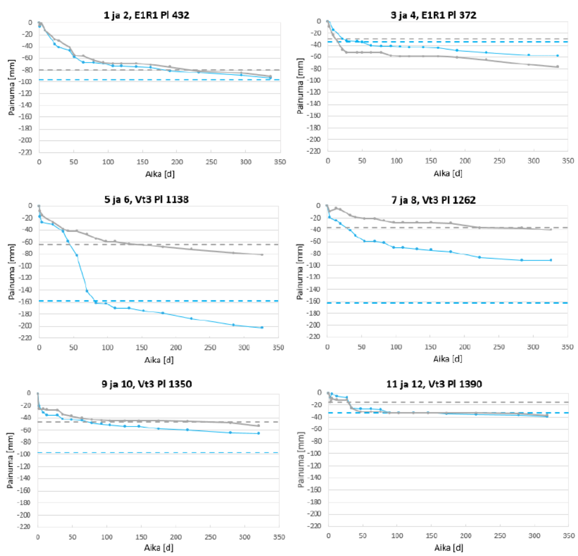

Figure 10. Measured settlements and calculated settlements (horizontal lines)

It was shown that the calculated primary consolidation settlements were in the correct order of magnitude when compared to the most recent measurements on site. The inaccuracies in the calculations resulted from soil parameter uncertainty, existing ground surface inaccuracy and from ignoring secondary consolidation.

3.3 *Monte Carlo simulation*

Monte Carlo simulation was also tested using real BIM-surfaces. Simulations were made by varying the compression index of clay layers, the pre-overburden pressure of clay and the depth of groundwater surface. The compression index of clay layers was varied using a log-normal distribution. The parameters for the distribution were given as means interpreted from laboratory tests with a coefficient of variance of 40 % for each layer. The variation of pre-overburden pressure and depth of groundwater surface was modeled by using triangular distributions for error terms that was added to the respective original values in each simulation. Figure 11 shows the measured settlements, means and 5 % and 95 % fractiles of calculated settlements.

Figure 11 demonstrates the uncertainty in soft soil settelement calculations. From Figure 11, it can be estimated that using single values for parameters (e.g. mean of laboratory tests) the possible settlement calculation error can be as large as +- 50 %.

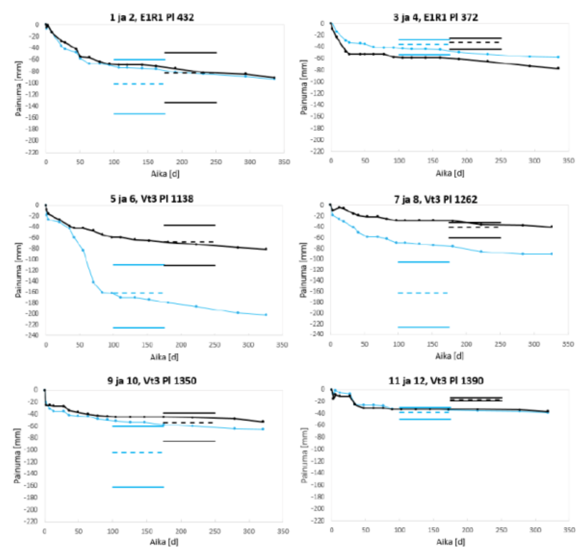

Figure 11. Means and 5 % and 95 % fractiles of calculated settlements (horizontal lines)

3.4 *Assumptions and limitations*

The BIM settlement calculation engine was implemented using the well known compression index method. Although the calculation model is formed three-dimensionally according to the BIM-model, it is assumed that the subsoil is in vertical one dimensional stress-strain state. Therefore, when the loading is narrow compared to the thickness of the deforming soil layer, the results may be very inaccurate as the assumption of one dimensional compression is not accurate.

In addition, the stresses are calculated using the Boussinesq theory of point loading, where the stiffness differences of the subsoil do not affect stresses due to loading. In many cases, where settlement calculation is relevant, the dry crust layer above groundwater surface is relatively stiff compared to the soil below and therefore the stress distribution in the soil may be different from the Boussinesq theory.

With the prototype version of the BIM settlement calculation engine, it is only possible to calculate the final values of primary consolidation settlements. Time-settlement behavior cannot be estimated with the current version of the program. Furthermore, initial and secondary settlements are ignored in calculations.

4 CONCLUSION

Infrastructure design processes are increasingly involving BIM-models with triangulated surfaces representing different earth structures and existing soil. Therefore, it is beneficial to develop geotechnical design tools which can use the BIM-model as input for geotechnical analysis.

The BIM settlement calculation engine described in this paper is intended for preliminary analysis of the feasibility of an embankment without soil improvement. Areas of excessive settlements are easily recognizable as the resulting settlement heatmap shows settlements over the whole calculation area, instead of only selected cross sections. The results can also be imported back into the BIM-model and examined within the model. This is not possible with conventional 2D cross-section calculation software.

The soil parameteres cointain major uncertainty. The reliability of the calculation results can be quantified using the Monte Carlo simulation implemented into the engine. It should be noted that emphasis should then be taken into determining the distributions of parameters, as the resulting settlement distribution and range is directly dependent on the variation of initial data.

The prototype version includes only the calculation of final primary consolidtaion settlements. Time-settlement behavior is not calculated. With further development, this could be added to the calculation program.

In the BIM settlement calculation engine it is assumed that the deformations are one-dimensional. Since BIM-models are three-dimensional, the calculations could also be executed fully three-dimensionally. Therefore, the development trend could be towards 3D-FEM -calculations directly with the BIM-model.

5 ACKNOWLEDGEMENTS

The author would like to thank Veli-Matti Uotinen from Finnish Transport Agency (FTA), Professor Leena Korkiala-Tanttu from Aalto University and Mikko Suoranta and Juha Liukas from Sitowise Oy. The author is grateful for the financial support of the FTA.

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