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# Automating stability analysis using BIM-FEA-Integration

## L'automation d'analyse de la stabilité employant l'intégration du BIM envers la FEA

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**ABSTRACT**: This paper examines chances and frontiers of BIM-to-FEA integration for geotechnical projects using a real-world excavation pit project underscoring its practical applicability. A BIM model is first created, which includes the urban context, the subsoil, the excavation pit, and the building to be erected. Elements relevant to the numerical model are identified, pre-processed and transferred to the FEA software leveraging an interactive automation routine. After the calculations and stability analysis, the results are back-transferred to the BIM model, which triggers an update routine for geometries and properties of the BIM model's objects enabled by their parametric definition. It is demonstrated that 2D numerical models can be derived from a complex BIM model. Strict adherence to the model structure and the establishment of appropriate modelling rules are prerequisites for this. The approach allows real-time interaction between BIM and FEA with automatic compliance of the stability. The developed automation process shows potential for efficiency gains, particularly in variational analyses and supports version control and data consistency.

**RÉSUMÉ**: Ce papier étudie les opportunités et les frontières pour l'intégration du BIM envers la FEM dans les projets géotechniques, en utilisant une fouille réelle, ce qui souligne l'applicabilité pratique. En premier lieu, une modèle BIM est créé, qui inclut le contexte urbain, le sous-sol, la fouille et le bâtiment à construire. Les éléments qui sont nécessaires au modèle numérique sont identifiés, prétraités et transférés au logiciel de FEM pour être tirés d'une routine de l'automation interactive. Après avoir effectué les calculs et l'analyse de la stabilité, les résultats sont transférés de retour au modèle BIM, que déclenché la routine de mise à jour pour les géométries et les attributs des objets du modèle BIM, causée par leurs définitions paramétriques. Il est démontré que les modèles numériques bidimensionnels peuvent être dérivés d'un modèle BIM complexe. L'adhérence élevée à la structure du modèle et l'établissement des règles appropriées pour la modélisation sont un prérequis pour ceci. L'approche permet d'interagir de temps réel entre le BIM et la FEM avec la conformité automatique de la stabilité. Le process d'automation qui est développé dans ce papier permet aux les gains efficients, notamment pour l'analyse variationnelle, et avalise le contrôle de version et la consistance de data.

**Keywords:** BIM; FEA; automation; integration; analysis.

## 1 INTRODUCTION

Building Information Modelling (BIM) exerts significant influence on the digitization of the AEC sector. Its model and data centric approach is increasingly adopted in geotechnical projects. In current practice, geotechnical design analysis is usually performed in separate, disconnected models. BIM models as well as analysis models frequently change during early project stages due to information gain and design changes. Such changes in one domain could potentially affect the validity of other domains models. After each change, the validity should be checked and evaluated. Due to the data isolation in the traditional process of design analysis, the evaluation and adjustments have to be done manually, which is flexible, but laborious and error prone.

To address these shortcomings a fully automated workflow integrating BIM and Finite Element Analysis (FEA) for stability analysis is proposed.

## 2 METHODOLOGY

The proposed process consists of the following steps: (I) Create a highly parametric BIM model, (II) extract and evaluate parameters needed for design analysis from the BIM model, (III) create two-dimensional (2D) FE model and calculate, (IV) dimensional optimisation, here using the Differential Evolution Algorithm (V) update BIM models using calculation results. Between each step, a version-controlled JSON-file is created, which is then used to trigger the next step and to evaluate, if a modification in one model affects the other one.

The implementation uses *Seequent Leapfrog Works, Autodesk Revit* and *Robert McNeel & Associates Rhino.Inside* for creating and managing the BIM models and *Bentley PLAXIS 2D (Version 2023-2)* for the numerical analysis. A python-webserver is used for data processing and transferring.

The developed process is validated and evaluated using a slightly adapted real world case study. The investigated excavation pit is located in an urban area in northern Germany and has been numerically investigated in (Jürgens & Henke, 2022). The therein listed numerical parameters are also used in the present study.

# 3 IMPLEMENTATION AND CASE STUDY

## 3.1 Parametric BIM models

In parametric modelling, in contrast to direct modelling, geometries are described by parameters and constraints. Editing such parameters results in an accordingly updated geometry. BIM authoring tools usually differ between components and a project layer, whereby the components tend to be more parametric.

The model granularity and the parametric logic needs to be set up in a way, that the results from the numerical calculation can update the BIM model. For example, if a calculation objective is to optimize the length of each diaphragm wall lamella, the lamellas need to be modelled individually and their geometric extents shall be driven by a corresponding length parameter.

The BIM models for the present case study are introduced in (Beck & Henke, 2023b) and are further developed for this contribution. Figure 1 shows a 3D view of selected coordinated BIM models.

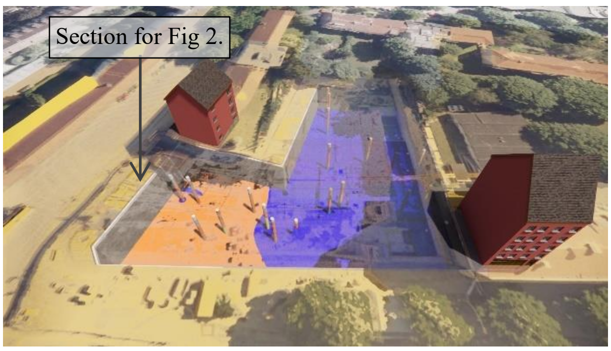



*Figure 1. 3D view of coordinated BIM models.*

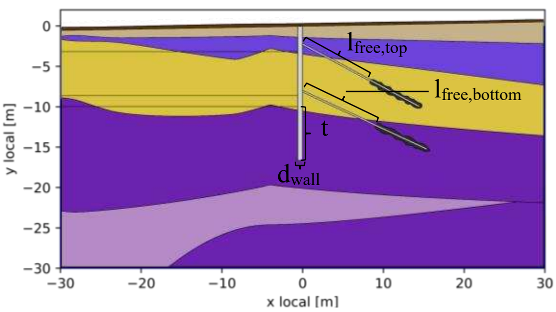
## 3.2 Data extraction and evaluation

The derivation of the plain strain 2D FE model follows the approach introduced in (Beck & Henke, 2023a). Given the problem definition, which is the stability analysis of a diaphragm wall here, the BIM models and other data sources are queried for relevant content. It is differentiated between elements, that are represented in the numerical model by one-dimensional elements (anchors, wall, etc.) and two-dimensional elements (soils) as well as boundary conditions and material properties. This is made possible by the underpinned semantic model and a rule-based system that evaluates how each element is represented in the FE domain. This approach allows the integration of additional expert knowledge with little effort.

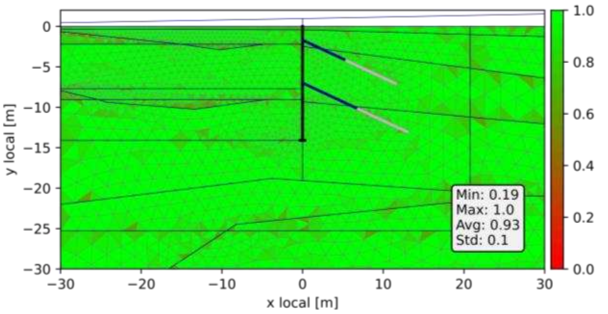
In the following, selected major steps in the developed process are outlined. Whilst many optional parameters can be set, the necessary inputs for the automation are location and type of analysis to conduct. A plane cutting the diaphragm wall perpendicularly at the point to be calculated is created. The resulting polylines of this plane's intersection with the 3D meshes that represent the soil volumes in the BIM model require further processing, as they cannot be directly used for meshing due to tiny segments and angles as well as small gaps between adjacent polylines. Besides that, they do not consider the construction sequence and the limited model area in the numerical domain. To address this issue, Boolean operations and topologically aware simplification techniques are applied as described in (Beck & Henke, 2023a). Figure 2 a) shows an exemplary cross-section through the subsoil model and the diaphragm wall with projected anchors. The width of the section used for the numerical analysis is 90 m, the depth is 50 m. Before the simplification, 19 closed polylines with 4983 control points are present in this area, of which 2593 are unique, meaning no other point is at that location. These polylines are not suited for mesh creation, due to small segments, small angles and little gaps between adjacent regions. After simplification, 17 polylines with 108 points (38 unique) remain. These can be then be used for mesh creation, see Figure 2 b). Multiple evaluation metrices and simplification algorithms ensure good mesh quality. The displayed mesh quality is calculated as ratio of the radius of outer to inner circle of a triangle, normalized to an equilateral triangle resulting in a minimal value of 0.19. The information for material creation in the 2D model is collected from the derived object and adjacent objects in the BIM model, e.g. for calculating anchor distance, as well as from external data sources where geometrical and non-geometrical information are considered. Throughout the whole process the relationships between the objects in the BIM model and its derived counterparts in the numerical model are maintained.

All information required for creating the numerical model is merged in one structured, human- and machine-readable text file using the JSON-format. This file is updated periodically and after certain events and is version controlled. If changes are found and a calculation in this scope already exists, the calculation is not compliant with the BIM model anymore and has to be recalculated. This information is displayed in a project dashboard, where all calculations are listed and managed. Depending on the number of numerical simulations and their computation times it might not be sensible to trigger a recalculation on changes instantly. The proposed procedure allows to evaluate changes prior to recalculation, so if only minor changes occur, a recalculation can be omitted. The file and the update scripts are designed to minimize the effort in recalculations, e.g. if no discretized geometry is changed, no meshing procedure is conducted.

*a) Cross section from the BIM model at the point of interest, with diaphragm wall and projected achors*




*b) Optimized geometry and resulting mesh quality in the FE model*




*c) Incremental strains $\Delta\gamma_s$ after strength reduction and optimization*

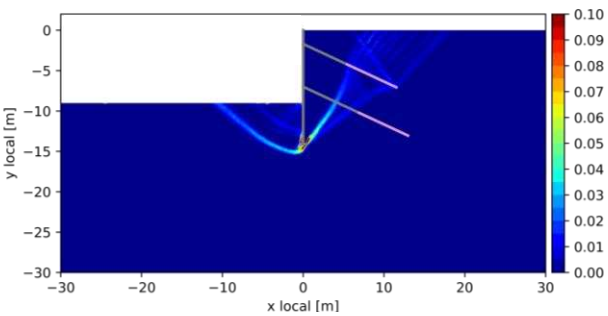



*Figure 2. Processing and calculation of an exemplary cross-section*

## 3.3 FE model creation and stability analysis

The named JSON-data is used to trigger the model creation routines which utilize the API provided by the used numerical software. The model creation follows these main steps: (I) Create materials, (II) create geometries, (III) assign materials to the geometry, (IV) generate mesh, (V) create construction sequence via calculation phases, (VI) assign hydraulic / thermal flow conditions. After the model has been created and calculated, strength reduction method for the surrounded soil is conducted and the resulted Factor of Safety (FoS) is stored. The implementation allows for real time interaction between the used programs, for example if the wall thickness needs to be adjusted, the corresponding parameter can be set in the BIM authoring tool and the corresponding parameters in the numerical model are updated immediately.

The soil parameters for the numerical model were realistically determined within the context of an inverse parameter calibration based on inclinometer measurements (Jürgens & Henke, 2022). As a constitutive model, the Hardening Soil Small model is employed, considering hardening plasticity and small strain stiffness. The information on the material parameters used for the soils, the diaphragm wall and the tie-back can be found in (Jürgens & Henke, 2022). The dimensions of the structures for the investigated excavation pit are based on preceding calculations using the limit equilibrium method (LEM) using BLUM's method. Due to the advantages of FEA compared to LEM, such as near-realistic constitutive models and soil-structure interaction behavior, system reserves are probably available. Therefore, the stochastic optimization algorithm, Differential Evolution (DE), originally proposed by (Storn & Price, 1997), is used. The statically required embedment depth $t$, the free anchor length of the two tiebacks $l_{\text{free}}$ and the diaphragm wall width $d_{\text{wall}}$ are optimized by creating a population with $n = 4$ adjustable parameters that is iteratively improved on the basis of evolutionary processes. Minimizing the FoS as a result of the strength reduction method serves as the objective function for DE. Therefore, it has to be noted, that this procedure does not find an economic solution. For the optimization process, the dimension of vectors used in DE $D$ is set to 5, from which the population size $m = D \cdot n = 5 \cdot 4 = 20$ is calculated. The implementation of DE for the numerical model is done using the *scipy* library with Python.

Figure 2 c) displays the results of the strength reduction method for the optimized condition in the form of incremental strains for the section highlighted in Figure 1. After a total of 320 calculations, respectively 16 iterations, the following optimized parameters for the dimension of the excavation pit wall are obtained $t_{\mathrm{DE}} = 4.17$ m, $l_{\mathrm{free,top,DE}} = 8.40$ m, $l_{\mathrm{free,bottom,DE}} = 8.24$ m, $d_{\mathrm{wall,DE}} = 0.69$ m with an minimized Factor of Safety $FoS = 1.18$. Table 1 compares this solution with the initial configuration and indicates optimization potential; see Section 4 for a discussion of practical applicability.

*Table 1. Parameters before and after optimization.*

| | **Before Optimization** | **After Optimization** |
|---|---|---|
| t [m] | 6.70 | 4.17 |
| $l_{\mathrm{free,top}}$ [m] | 9.60 | 8.40 |
| $l_{\mathrm{free,bottom}}$ [m] | 10.40 | 8.24 |
| $d_{\mathrm{wall}}$ [m] | 0.60 | 0.69 |
| FoS [-] | 1.66 | 1.18 |

### 3.4 Update of BIM models

A routine to analyse the calculation results is triggered, when a new version of the output files created by the numerical software is saved. In addition to default ones, results based on the problem definition are parsed and stored in a separate JSON-file. This file is also version controlled as descried above. If changes are detected, a routine updating the BIM models starts.

In the present case study, the main optimized parameters, that are transferred back to the BIM model, are the anchor lengths as well as the width and the embedment depth of the diaphragm wall. As the corresponding BIM objects are modelled parametrically, only the belonging parameters need to be set and the geometries and derived evaluations update automatically. It is also documented how a parameter is set – either as a result from a changed calculation or another way, e.g. manually. As a result, a re-calculation of the model directly after it has been calculated is avoided. Additional results, such as the FoS, displacements and moment distributions can be set directly assigned to BIM models or by reference, which is preferable for bigger datasets.

## 4 CONCLUSION AND OUTLOOK

A conceptual BIM-FEA-Integration framework based on commonly used software tools was introduced. It allows for fully automated derivation of 2D-FE models, their calculation and the update of the parametric BIM models based on simulation results and dimensional optimization. The consistency between the numerical models with the BIM models is continuously verified, which is enabled by version-controlled text files that are used to transfer data between process sections. The conducted case study shows that the developed procedure is robust and that complex site conditions can be adequately considered. The conducted stability analysis using strength reduction method proved suitable as a possible method for optimizing design relevant geometric parameters. The used geometry evaluation metrics and simplification techniques and metrices are going to be published separately.

Future endeavors shall strive to more standardization which is supposed to increase efficiency gains and reduce entry thresholds for practitioners. Investigations on the suitability of different optimization techniques and objectives and considering more parameters are also promising to increase the practical applicability. If a single objective optimization technique is applied for real world problems, it is feasible to use an economic evaluation as the objective function instead of the FoS and use the FoS as a constraint.

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