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Research paper

Analysis of soil-structure interaction using 2D/3D FEM calculations in geotechnical design

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Abstract: Geotechnical design is a complex, interdisciplinary field involving soil science, mechanics, and rheology. This article presents a comprehensive solution for geotechnical design using digital data from various programs, focusing on Ultimate Limit State (ULS) and Serviceability Limit State (SLS) analysis for a storage hall foundation in challenging geotechnical conditions in eastern Germany. The study utilizes the groundwater conditions and layer layout from the Leapfrog software to create a spatial computational model of the subsoil using Plaxis 3D FEM based on nearly 400 virtual boreholes. Data on hall geometry and load combinations were stored in digital IFC format and tabular data in Excel files respectively. The analysis involved both analytical and FEM 3D/2D methods. In the analytical method, all digital information was collected into one Excel file database for further calculations. Once the consistent digital project database was collected, the same data was implemented into the Plaxis 3D program for FEM numerical calculations. The hall's foundation solution used footings supported by drilled piles. Soil layer parameters were calibrated based on static pile tests during design calculations. Due to part of the hall being located in a high embankment area (about 5 meters high), consolidation analysis of cohesive soils in the area was considered. The impact of consolidation was factored into negative skin friction in the ULS pile design process. Pile geometry was tailored to existing soil conditions and weak bearing soil thickness. The final foundation geometry and pile lengths were designed to meet SLS conditions set by the structural designer and to address uneven building settlement.

Keywords: digital data, AGS, FEM analysis, geotechnical design, Plaxis 3D, soil-structure interaction

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1. Introduction

This study provides a comprehensive computational and design analysis of the foundation of a logistics center building (industrial hall) to be built in the northwestern part of the Berbersdorf industrial park.

The computational analysis was carried out based on analytical methods [1, 2], and numerical modeling in Plaxis3D. After verifying the level of convergence of the two methods, the geometry of the footings and the number and length of piles were designed. The above analysis allowed to meet the Serviceability Limit State (SLS) and Ultimate Limit State (ULS) required by the contracting authority.

The paper by Kacprzak and Bodus [3] describes various possibilities for making use of digital soil information obtained from field and laboratory tests, stored in one of the proposed digital formats – AGS. Boruc et al. [4] propose an alternative approach by using digital data as the primary source of information. This form of operation makes it easy to build a digital model of information about the geometry and parameters of the soil.

This article was created to provide a comprehensive overview of tools for working with a large amount of digital data. It explores the collaborative use of software such as Leapfrog – Plaxis, Revit/CAD 3D – Plaxis, as well as Robot Structural – Plaxis to facilitate mutual cooperation. This exploration seeks to provide a comprehensive understanding of how these tools can be employed to facilitate effective collaboration in managing large digital datasets. Some information related to the information flow of BIM – FEM modeling is described in detail, for example, in [5, 6].

2. Workflow process

This paper presents an analysis of the interaction between a digital database of three basic databases, i.e. geology, construction, impacts (loads). The process of digital information flow is shown in Fig. 1 the creation of a comprehensive geotechnical model, incorporating all

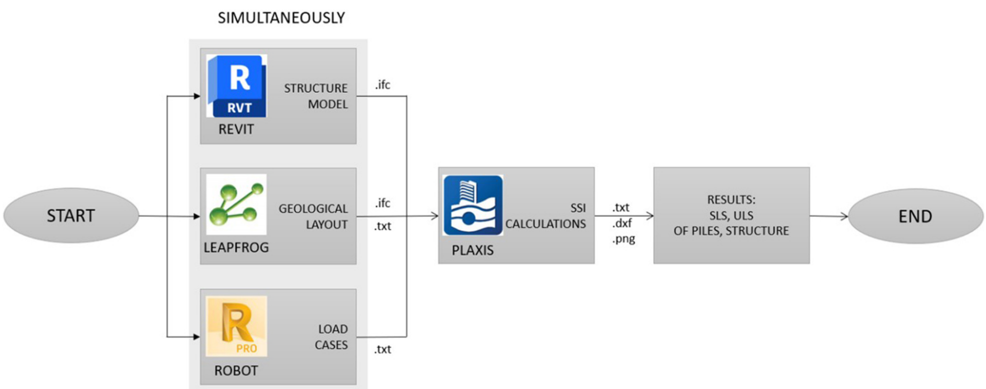


Fig. 1. The geotechnical design workflow process

three databases (geology, construction, impacts), proceeds simultaneously. The digital ground model was built in Leapfrog software, which has appropriate modules for managing geological data. The building structure was modeled in the Revit program (an environment using BIM modeling technology). Interactions with various load cases and combinations were collected in Robot Structural Analysis Professional (ARSAP). The Plaxis 3D program for advanced FEA calculations allows an intuitive way to combine all three of the above-described databases so that SSI (Soil-Structure Interaction) can be performed, and structures can be designed correctly. Kacprzak and Bodus [3] proposed an alternative approach that also uses parametric modeling and model verification of model geometry. For more interesting and practical information on collecting and managing geotechnical data in various industry environments, see [7, 8].

2.1. Geological model of the soil layer layout

To create the geological database Leapfrog Works software was used. Leapfrog Works is geological and engineering software that enables three-dimensional modeling and analysis of geological data. It is used for creating geological models, mine planning, terrain stability analysis, and geological risk assessment. Leapfrog Works allows the integration of geological data from various sources such as drillholes, geophysical surveys, and geological maps, enabling comprehensive analysis of the geological structure of an area.

Once the geological 3D model is finished, the software allows users to export geological data in various data formats (i.e. Elevation/Thickness Grids as Arc/Info ASCII Grid Files or Borehole Data as CSV Files and IFC Files (v4).

In the absence of access to Leapfrog software, less advanced geological databases such as the popular OpenGround Professional or GeoDin can be used to create a geological database that can be imported into Plaxis 3D. These programs allow users to export data in many different formats, including export of all data grid views to XLSX, XLS, TXT or export of data sequences to CSV.

If it is not possible to use a digital database, it is possible to use data in AGS format obtained from the geological investigation contractor. Data in AGS format can be easily converted to Excel spreadsheet by using Key-AGS and then processed by the user as required.

The spatial geological model in 3D Plaxis was prepared using information from Leapfrog, which was effortlessly obtained due to the prior preparation of a 3D model of ground conditions based on field investigation and laboratory testing, allowing Leapfrog to visualize the space between boreholes and create a layering system. The soil model from Leapfrog (IFC file; the view from IFC browser) is shown in Fig. 2.

Firstly, in order to effortlessly transition the geometry of the geology from Leapfrog to Plaxis 3D, nearly 400 virtual boreholes were created at the locations of the designed foundation pads. The generated data was tabulated in Excel. An example view of a spreadsheet containing data on the soil layers in the virtual boreholes for each foundation is shown in Fig. 3.

Construction of a Plaxis 3D soil model based on selected virtual boreholes is shown in Fig. 4. The ground area was divided into two zones – the “plasticity zone” and the “rock connection”.

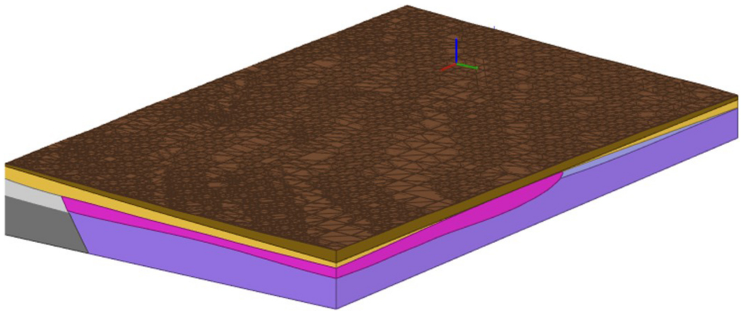
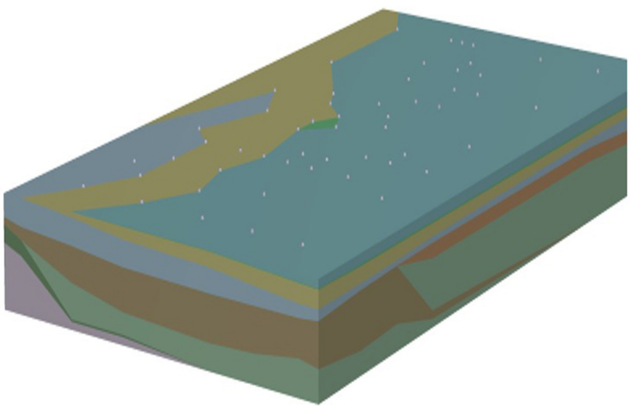


Fig. 2. Soil model from the Leapfrog

	A	B	C	D
1	holeid	from	to	20230414 Berbersdorf
2	SFO-001	0	5.327	
3	SFO-001	5.327	5.822	'Organic layer'
4	SFO-001	5.822	7.797	'Flowing soil'
5	SFO-001	7.797	14.784	'Weathering clay'
6	SFO-001	14.784	30	Clay slate, weathered
7	SFO-002	0	5.048	
8	SFO-002	5.048	5.569	'Organic layer'
9	SFO-002	5.569	7.759	'Flowing soil'
10	SFO-002	7.759	14.333	'Weathering clay'
11	SFO-002	14.333	14.355	Clay slate, decomposes (tsf,zg)
12	SFO-002	14.355	30	Clay slate, weathered

Fig. 3. Soil layers data exported from Leapfrog



Legend		
0	Embankment	
1	Organic layer	
2	Flowing soil	
3	Weathering clay	
4	Clay slate, decomposes	
5	Clay slate, decomposes plastically	
6	Clay slate, weathered	
7	Greywacke, decomposed	
8	Greywacke, weathered	

Fig. 4. Soil layers data exported from Leapfrog

2.2. Building structure model

For the structure model preparation Revit software was used. Revit is a powerful Building Information Modeling (BIM) software, widely used in the architecture, engineering, and construction industries. It allows users to design, model, and document building projects in a 3D environment, enabling the creation of intelligent and coordinated digital representations of the building's components. Revit allows for the creation of three-dimensional building models in a parametric manner, meaning changes to one element automatically affect related elements throughout the project.

Revit allows users to easily integrate with other programs by allowing simple export of the modeled structure. The model created in Revit should be exported to Plaxis 3D in IFC or step format. Some information related to the flow of information in BIM – FEM modeling is described in detail, for example, in [5, 6].

2.3. Load cases and combination interactions

Robot Structural Analysis Professional (ARSAP) software was used to check and model the interactions with different load cases and combinations. Robot Structural Analysis Professional is a comprehensive software tool for structural analysis and design. It is widely used by structural engineers and designers to simulate and analyze the behavior of a wide variety of structures, including buildings, bridges, and other civil engineering projects. ARSAP offers advanced capabilities for finite element analysis (FEA), enabling users to model and simulate the behavior of complex structures under various loading conditions. The software allows for the analysis of structural response to static, dynamic, and nonlinear loads, as well as the assessment of structural stability and performance.

Once the load cases and combinations have been determined, the software offers the possibility of exporting the data in several different formats. To easily import them into Plaxis 3D, data can be exported in txt/csv format.

3. Information about the project

In this chapter, it is shown how soil parameters were calibrated based on the results of pile load test. Soil deformation modulus, skin friction resistance values and the base resistance of the pile were calibrated. In addition, an estimation of the impact of the construction of the high embankment, on which the designed hall will be founded, on the designed foundation is shown. This influence was considered as negative friction on the piles.

3.1. Calibration of the soil parameters based on the Static Load Test (SLT)

In order to calibrate the strength parameters of the soil layers to the Plaxis model, the results of STL – pile test loading were used. Pile load tests were performed in two different zones, i.e. the "plasticity zone" and the "rock connection zone". The testing load zones were modeled in the Plaxis 3d model. The results were also used to calibrate the pile skin friction resistance and the pile base resistance. In the Table 1, the parameters of soil subsoil from the given design documentation are shown.

Drilled piles of the CFA type with a diameter of 880 mm were subjected to test loading. The lengths of the piles were selected according to the location of the selected zones of the geological layer system and were 14 and 18 m.

The results of load-settlement curves of the pile head from SLT were used to calibrate the deformation parameters of the soil layers. The relationship is obtained from successive values of forces applied to the pile head, resulting in the value of pile head displacement. Simulations of static pile loads were mapped into computational models. A view of the 3D model with the layer system used for the test loads is shown in Fig. 5. A comparison of the load-settlement relationships results of the pile head is shown in Fig. 6.

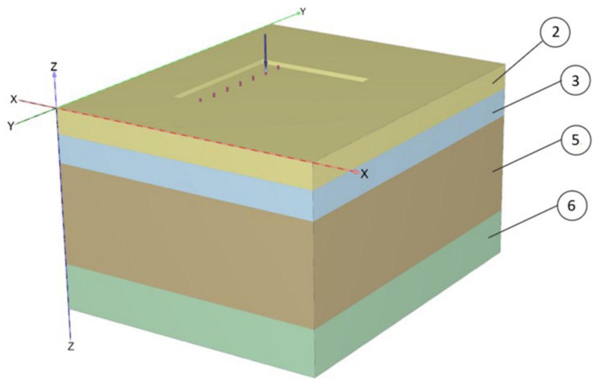


Fig. 5. Soil model in Plaxis 3D of the SLT; Layers 2 – Flowing soil, 3 – Weathering clay, 5 – Clay slate, decomposes plastically, 6 – Clay slate, weathered

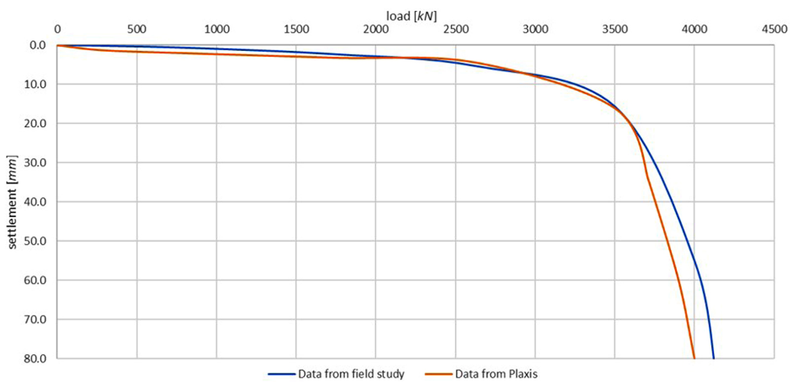


Fig. 6. Diagrams of relationship between settlement and applied load in the pile P1.2. Field test blue line. Plaxis test orange line

To obtain convergence between the results from the SLT and the modeled results the calibrated parameters were used: stiffness modulus of concrete in the pile – $E = 30$ GPa, higher modulus of soil – clay slate decomposes – $tE = 90$ MPa, higher modulus of soil – clay slate weathered – $E = 220$ MPa, higher unit limit of pile skin friction resistances and unit limit of pile base resistance: layer no. 4 $q_{sk} = 90$ kPa (constant value), for layer no. 6 $q_{sk} = 220$–300 kPa (linear relationship), $q_{sk} = 4900$ kPa. The initial and calibrated values of soil parameters are shown in the Table 1. The posted values are close to those recommended by [2].

Table 1. Soil model from the Leapfrog

No.	**Layer**	**Floor group according to DIN 18196**	**Degree of weathering (DIN EN ISO 14489)**	γ **(kN/m^3)**	γ' **(kN/m^3)**	φ' **(°)**	c' **(kN/m^2)**	E_s **(MN/m^2)**	$q_{s,k}$ **(kN/m^2)**	$q_{b,k}$ **(kN/m^2)**	k_f **(m/s)**
1	Oberboden Organic layer	OU, OT, TL		17	7	25	0	1	0	0	1×10^{-7} to 1×10^{-9}
2	Fliesserde Flowing soil	UL, TL, TM		19	9	25	2	5	53	0	1×10^{-8} to 1×10^{-9}
3	Verwitterung-slehm Weathering clay	UL, TL, TM		19	9	25	5	8	53	0	1×10^{-8} to 1×10^{-9}
4	Tonschiefer zersetz Clay slate decomposes	SU, SU*, GU, GU*	V4–V5	20	10	(27.5) 30	10	(30) 90	(76) 90	1.600	1×10^{-7} to 1×10^{-8}
5	Tonschiefer, zersetz-plastisch Clay slate, decomposes plastically	local TL, TM, TA	V3–V5 Local plastic zones	20	10	27.5	5	25	76	1.250	5×10^{-9} to 1×10^{-10}
6	Tonschiefer, verwitter Clay slate, weathered	–	V2–V3	21.5	11.5	(27.5) 30	50	(150) 220	(200) 220–300	(2.500) 4.900	5×10^{-7} to 5×10^{-8}
7	Grauwacke, zersetzt Greywacke, decomposed	SU, SU*, GU, GU*	V4–V5	21	11	35	0	50	120	3.000	1×10^{-6} to 1×10^{-8}
8	Grauwacke, verwitter Greywacke, weathered	–	V2–V3	24	14	35	30	300	300	5.000	1×10^{-6} to 1×10^{-7}

It is important to note that the calibrated averaged frictional resistance and soil parameters from the above analysis should be used for the next global calculations. After receiving the results, the internal forces in the piles and the pile head settlements should be verified. This has been described in more detail, for example, by Kacprzak and Bodus in [5]. The model tests were carried out on the basis of characteristic parameters. For the final dimensioning of the piles, the design factors should be considered according to PN-EN 1997 [1].

3.2. Consolidation

The calculations were performed taking into account the fact that the logistics center building will be built on an area requiring embankment construction. On half of the building there are layers of cohesive soils – "plasticity zone", on which the largest embankment will be built (about 5 m). On the other half of the building there is an expanse of weathered rock – "rock connection zone", and the area will be leveled (about 3.0 m).

The large difference in the stiffness of the subsoil at the foundation level leads to uneven settlement of the structure, which can lead to structural failure both during the construction stage and in the future. The view of this existing situation is shown in Fig. 7, and Fig. 8.

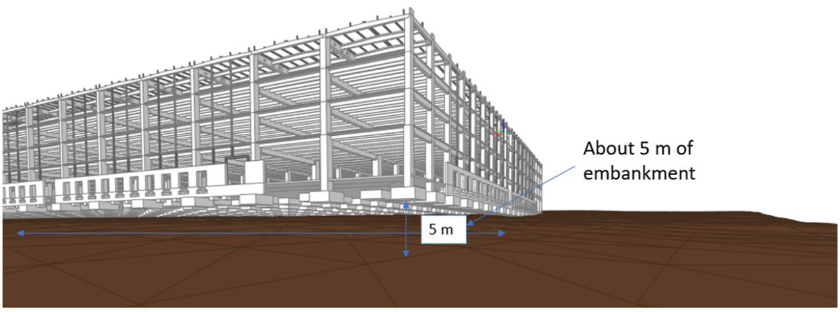


Fig. 7. 3D view of the foundation of part of the building on the embankment. The problem of consolidation of the embankment

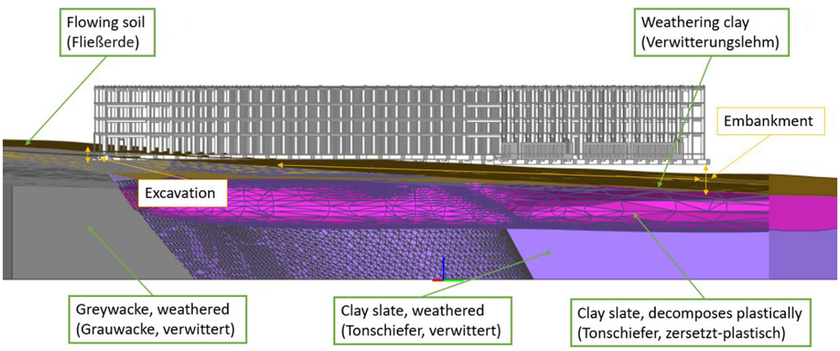


Fig. 8. Cross section through building and site geology; problem of embankment consolidation

Considering this risk, settlement calculations were carried out taking into account the consolidation time. The effect of consolidation settlement should be added in the form of negative friction in the pile calculations. The calibrated parameters of the soil layers described in Chapter 3, (3.1), Table 1, were used for the calculations. The directions of the filtration coefficients are isotropic. In numerical analysis the assumption as following formula was adopted:

$$k_x = k_y = k_z \tag{3.1}$$

For the calculation, soil data from the boreholes, that contains the most plastic soil compared to the height of the embankment was used. The layout of the soil layers and the computational cross-section was implemented into numerical model. Dimensions of the foundations foot: length 4 m; width 4 m; height 1.75 m (the dimensions are compatible with the initial foundation arrangements). Embankment height: 4.8 m.

It was assumed that the organic layer (0.5 m) will be removed and replaced by the material used for the embankment, and that the embankment will be built in fragments, each 1.2 high. For each piece it is predicted 30–60 days for consolidation. After the whole embankment is built, the consolidation calculation has no time limit, and is calculating until the minimum excess pore (1 kPa) is reached. This is to estimate the consolidation time and maximum foundation settlements from embankment. Figure 9 shows the model phases.

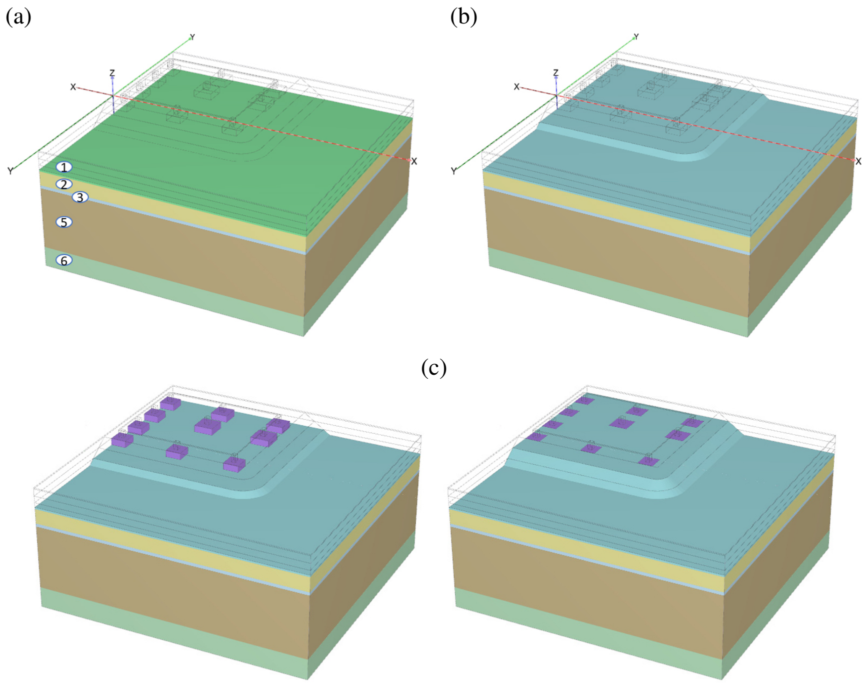


Fig. 9. Model construction phases: (a) Initial phase, (b) Replacing organic layer and building the first layer of the embankment (1.2 m hight), (c) Building the foundations and second layer of embankment (2.95 m hight); on the left picture the embankment layer is hidden for showing the foundation construction

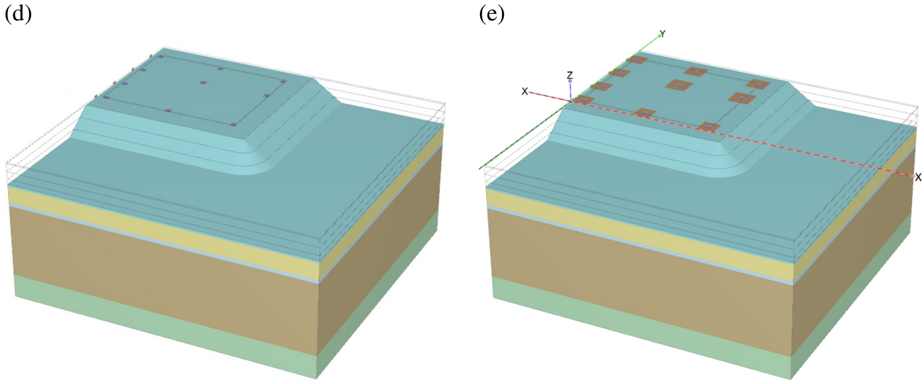


Fig. 9 [cont.] Model construction phases: (d) Building the foundations and third part of embankment (4.8 m hight), (e) Consolidation calculation until the minimum excess pore achieved

The result of this analysis is consolidation settlements. Figure 10 shows a 3D view in the form of total settlement map in the analyzed model. The variation of settlement over time is shown in graph form in Fig. 11.

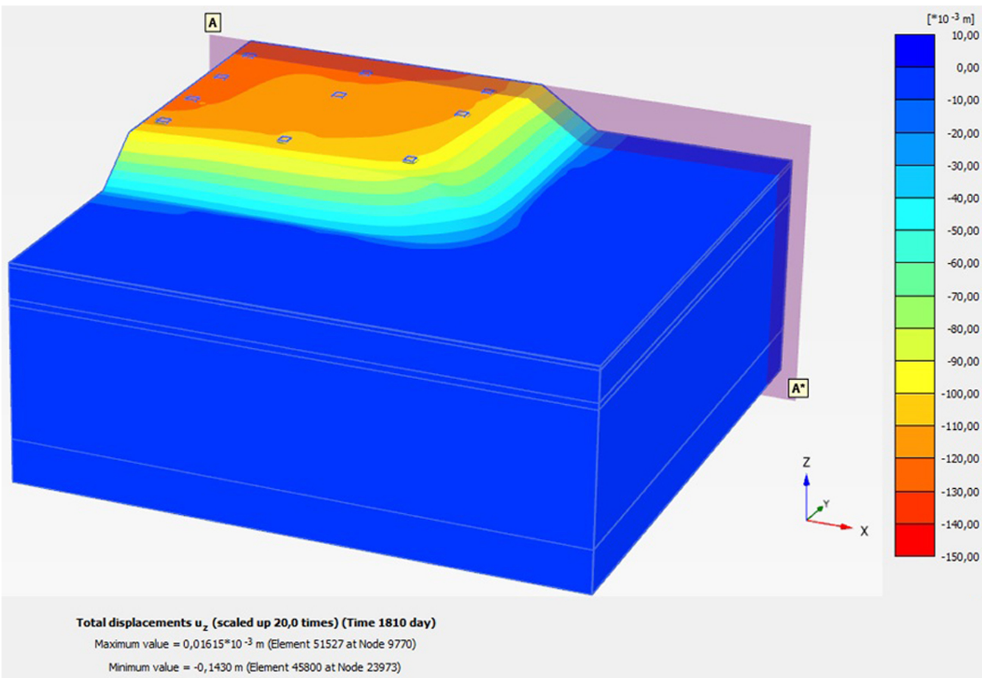


Fig. 10. 3D view of total settlement map

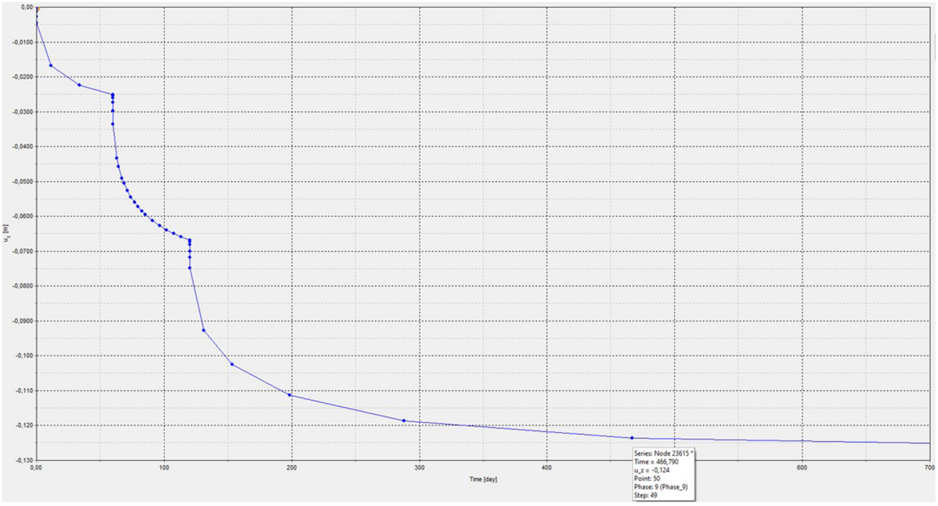


Fig. 11. The settlement variation over time (visibility range from 0 to 700 days)

After the consolidation process, which lasts about 1800 days, the total settlement is approximately 0.13 m (129 mm). The calculations show that total settlement mobilized at 96% (124 mm) will be reached after about 446 days (about 14 months). The settlement of 111 mm is reached after 202 days (about 6–7 months), which is at 86% of the value of full settlements.

Consolidation settlements resulting from embankment construction should affect pile design. Therefore, negative friction resulting from embankment settlement over time has to be included in the pile calculations. The model construction stage adopted should be updated with the time of embankment formation at the construction site. The obtained results of settlement mobilization time should be included in the construction schedule so that most of the settlement is mobilized during the embankment construction stage.

3.3. Design of piles

In PLAXIS 3D, piles were modeled as embedded beams, reflecting their structural integrity and load-bearing capabilities within the soil matrix. This modeling approach enables a comprehensive analysis of pile behavior under various loading conditions and soil layout variations. Due to the heterogeneous soil conditions and specified limit values of shaft and pile base resistance (refer to Table 1), a specific number of pile types were introduced. Nine distinct pile types were established primarily to accommodate the variability in soil conditions at the base of the pile. The total number of designed piles is 1531, with pile lengths designed to the existing soil conditions (a view of the piles by type can be seen in the Fig. 12).

Detailed results were obtained for each pile, including internal forces and reactions at the base of the pile. Based on the maximal internal forces, Ultimate Limit State (ULS) conditions were verified. The maximal resistance of piles was determined using analytical methods [1,2]. An example view of internal forces in a pile is shown in Fig. 13.

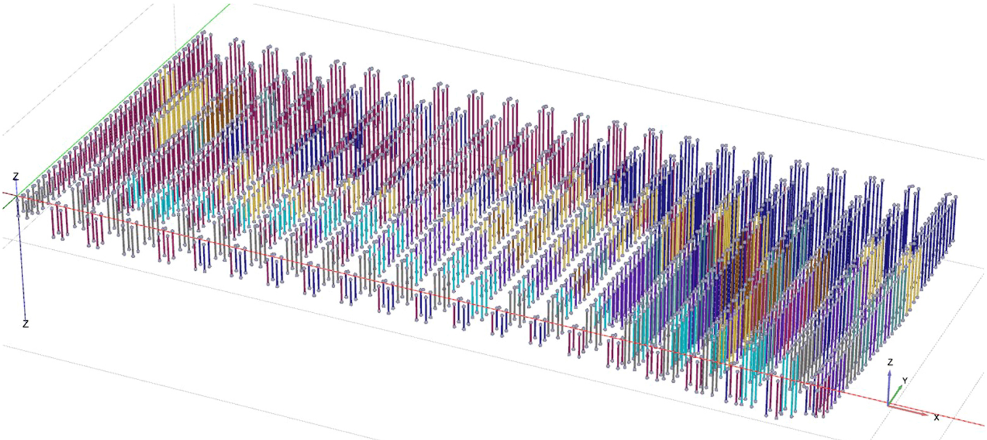


Fig. 12. View of pile types

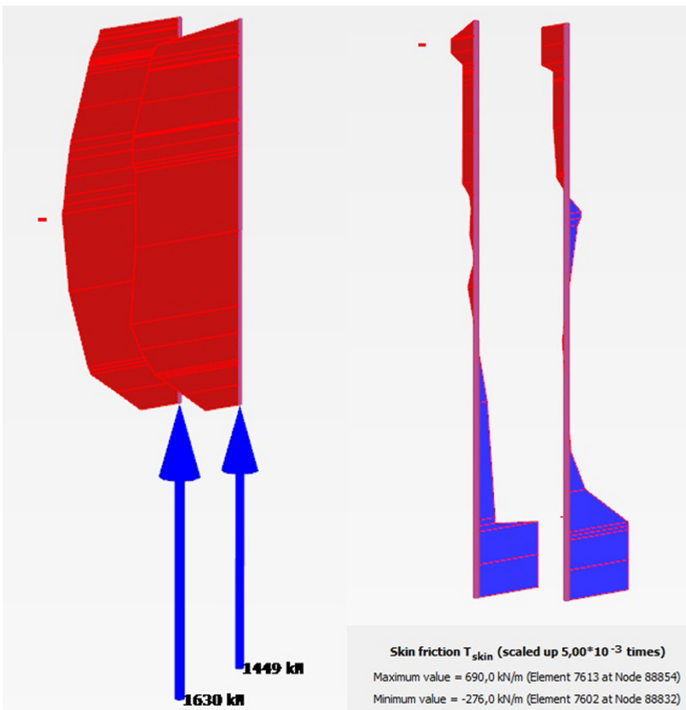


Fig. 13. Axial forces and skin friction for pile 1 and pile 2 in Plaxis 3D model

3.4. Settlement analysis

The settlement analysis serves as a critical component in assessing the stability and performance of the foundation and piles under applied loads. Through rigorous simulations and computations, the settlements of the soil matrix, foundation, and piles were meticulously evaluated across different loading scenarios. The results revealed the distribution and magnitude of settlements at various points within the soil matrix, providing valuable insights into the deformation characteristics and load-bearing capacity of the foundation-pile system. Finally in accordance to SLS (serviceability limit state) for settlement differences condition L/500 has been assured between each pad foundation. The results can be analysis in form of cross-sections and plan views as shown in Fig. 14 and Fig. 15.

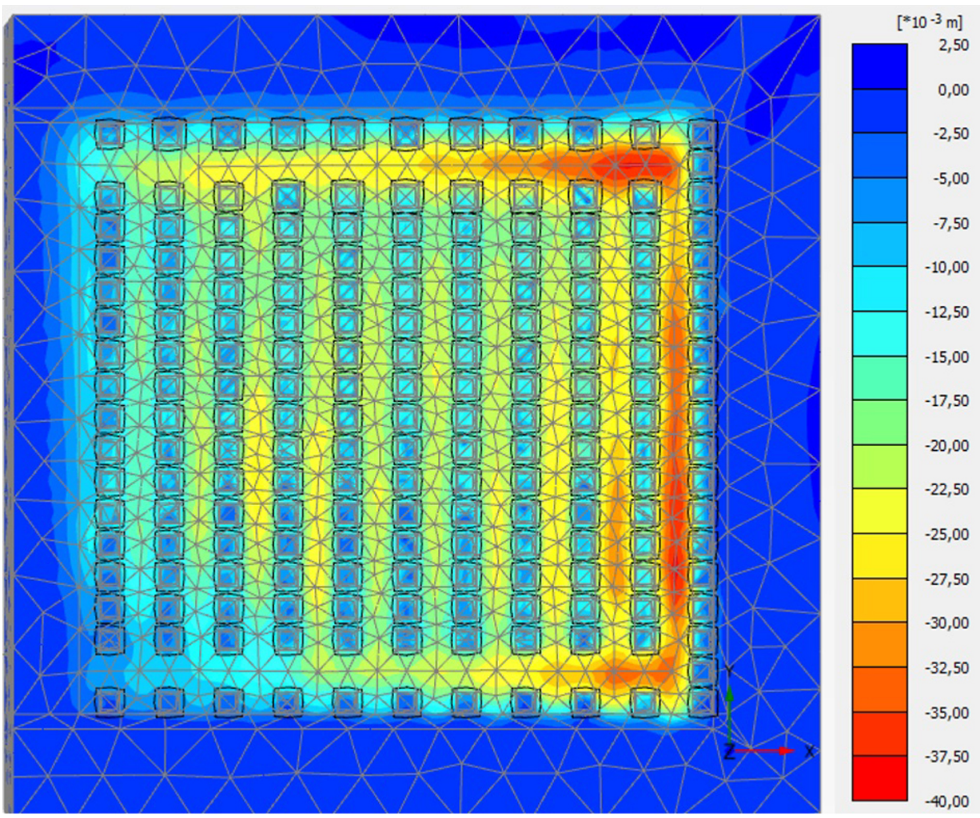


Fig. 14. Top view of vertical displacements of flooring and pad foundations

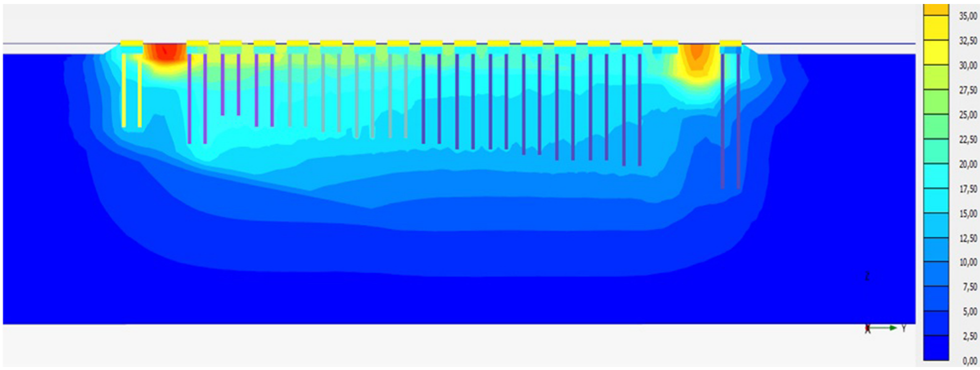


Fig. 15. Cross-sectional results of vertical displacements of soil matrix

4. Conclusions

The article presents a comprehensive example of geotechnical design in the case of having digital information of multiple design data from different calculation programs. The block diagram discussed (Fig. 1) shows the possible path for building a geotechnical calculation model in Plaxis 3D and what types of files should be used as input data.

Working on a large amount of data requires control of the information provided. Therefore, the analysis was performed in two ways, i.e. using analytical, computational empirical methods and computational 3D/2D FEM analysis. In the analytical method, all digital information was compiled into a single Excel database, where further calculations were performed. Once a consistent digital design database was created, the same information was implemented into Plaxis 3D software to perform numerical FEM calculations.

The foundation solution for the hall was designed using footing technology of dimensions of about 5×5 m with 5 foundation piles of 0.88 m diameter. The pile lengths were optimized and appropriately selected to meet the ultimate limit states according to [1]. The SLS condition imposed by the structural designer regarding the differential settlement of the footings was achieved. An additional result of the spatial SLS analysis was the information about the significant settlement of the soil under the floor between the footings. In the analytical approach, focusing only on the foundations, the result of floor settlement could have been ignored.

References

[1] PN-EN 1997-1:2008 Projektowanie geotechniczne. Cz. 1: Zasady ogólne. PKN, 2008.

[2] German Geotechnical Society (Deutsche Gesellschaft für Geotechnik e.V.), Ed. *Recommendations on Piling (EA-Pfähle)*. Ernst &Sohn, 2014.

[3] G. Kacprzak and S. Bodus, "Automatyzacja przepływu cyfrowej informacji w projektowaniu geotechnicznym", *Acta Scientiarum Polonorum. Seria: Architectura*, vol. 19, no. 2, pp. 31–39, 2020, doi: 10.22630/ASPA.2020.19.2.15.

[4] J. Boruc, G. Kacprzak, S. Bodus, and W. Kalisz, "BIM w geotechnice", *Materiały Budowlane*, vol. 566, no. 10, pp. 64–65, 2019.

[5] A.S. Birkemo, S.C. Hjortland, S.M. Samindi, and M.K. Samarakoon, "Improvements for the workflow interoperability between BIM and FEM tools", *WIT Transactions on The Built Environment*, vol 192, pp. 317–327, 2019, doi: 10.2495/BIM190271.

[6] G.R. Paul and M. Karthikeyan, "A Study of Interoperability Between BIM and FEM for Improved Structural Analysis and Design (Phase II)", *International Journal of Creative Research Thoughts (IJCRT)*, vol. 11, no. 10, pp. 100–134, 2013. [Online]. Available: https://ijcrt.org/papers/IJCRT21X0133.pdf. [Accessed: 25 Jan. 2024].

[7] N. Kajste, "Webinar: Connecting data and geotechnical teams", Ground Engineering. [Online]. Available: https://www.geplus.co.uk/news/webinar-connecting-data-and-geotechnical-teams-29-03-2023/. [Accessed: 25. Jan. 2024].

[8] "From local server to the cloud: How the Arcadis team transformed data management with OpenGround". [Online]. Available: https://www.seequent.com/from-local-server-to-the-cloud/. [Accessed: 25. Jan. 2024].

[9] G. Kacprzak and S. Bodus, "An analysis of the foundation of the highest building in the EU based on numerical modeling and pile load test", in *Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering (ECSMGE 2019)*. Reykjavik: The Icelandic Geotechnical Society, 2019, doi: 10.32075/17ECSMGE-2019-0850.

Analiza współpracy podłoża gruntowego z konstrukcją z wykorzystaniem obliczeń MES 2D/3D w projektowaniu geotechnicznym

Słowa kluczowe: dane cyfrowe, AGS, analiza MES, projektowanie geotechniczne, Plaxis 3D, interakcja grunt-konstrukcja

Streszczenie:

Projektowanie geotechniczne jest dziedziną trudną i interdyscyplinarną wykorzystującą gruntoznawstwo, mechanikę gruntów, mechanikę budowli, zjawiska reologiczne etc. Artykuł ma na celu zaprezentowanie kompleksowego rozwiązania projektowania geotechnicznego w przypadku posiadania cyfrowej informacji wielu danych projektowych pochodzących z różnych programów obliczeniowych. Praca dotyczy tematyki projektowania geotechnicznego z analizą stanów granicznych nośności i użytkowalności na przykładzie koncepcji projektowej posadowienia hali magazynowej w trudnych warunkach geotechnicznych wschodnich Niemiec. Wykorzystując informacje dotyczące warunków gruntowo-wodnych i układu warstw z modelu programu Leapfrog zbudowano przestrzenny model obliczeniowy podłoża w metodzie analitycznej i programie numerycznym Plaxis 3D MES bazując na blisko 400-stu wirtualnych odwiertach. Informacje na temat geometrii hali o długości 330 m i szerokości 150 m zapisana została w pliku ifc. Oddziaływania w postaci kilkunastu projektowanych kombinacji obciążeń na stopy fundamentowe z ich lokalizacją w globalnym układzie współrzędnych zostały zapisane w postaci danych tabelarycznych plików Excel. Analiza wykonywana była dwutorowo tj. z wykorzystaniem analitycznych, obliczeniowych metod empirycznych oraz obliczeniowej analizy MES 3D/2D. W metodzie analitycznej wszystkie cyfrowe informacje zostały zebrane w jedną bazę danych programu Excel, gdzie przeprowadzono dalsze obliczenia. Po utworzeniu spójnej cyfrowej bazy danych projektowych te same informacje zostały zaimplementowane do programu Plaxis 3D w celu wykonania obliczeń numerycznych MES. Rozwiązanie posadowienia hali zaprojektowano w technologii stóp fundamentowych posadowionych na palach wierconych. Na etapie obliczeń projektowych przeprowadzana została kalibracja parametrów warstw gruntowych w oparciu o badania statyczne pali. Z powodu posadowienia części geometrii hali na obszarze wysokiego nasypu (ok 5 m wysokości) w obliczeniach wykonano analizę konsolidacji gruntów spoistych występujących na projektowanym obszarze. Wpływ konsolidacji został uwzględniony w postaci tarcia negatywnego przy projektowaniu SGN pali. Geometria pali została dopasowana do panujących

warunków gruntowych, miąższości warstw słabonośnych. Ostateczna geometria fundamentów hali w tym długości pali zostały zaprojektowane, aby spełnić warunek SGU narzucony przez projektanta konstrukcji oraz wyrównać nierównomierne osiadania budynku.

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