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Process of analysis and design of deep foundations of fully automated warehouse in difficult soil conditions

Processus d'analyse et de conception des fondations profondes d'un entrepôt entièrement automatisé dans des sols difficiles

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ABSTRACT: Nowadays, the construction industry aims to ensure a consensus between costs and the reliability of the structure. The analysed object is a high storage fully automated warehouse with a footprint of approximately 120 x 50m, 35m high. High storage warehouses in connection with the strict requirements for total settlements and angular deflection of the foundation slab belong to the group of objects requiring an individual design approach. The soil conditions are complex, including peat (I_{om} > 50%), sandy soils layered with organic soils underlain with gyttja's (organic soil I_{om} ca. 30%) reaching to 100m below ground level. The above-mentioned construction in combination with local soil conditions creates an extreme design case. The article presents the process of elaborating a solution that enables safe foundation system, analysis of conducted test piles, applied construction models and summarizes the process of foundation implementation.

RÉSUMÉ: De nos jours, le secteur de la construction a comme objectif un consensus entre les coûts et la fiabilité de la structure. L'objet analysé est un entrepôt entièrement automatisé de grande hauteur, avec une superficie au sol d'environ 120 x 50 m et une hauteur de 35 m. Les entrepôts de grande hauteur font partie des structures nécessitant une approche de conception individuelle, du fait des critères stricts de tassement absolus et différentiels de la dalle de fondation. Les conditions du sol sont complexes avec notamment de la tourbe (Iom > 50%), des sols sablonneux alternant avec des sols organiques suivis de gyttia (sol organique à hauteur de 30% environ) atteignant 100 m sous le terrain naturel. La structure en question représente un cas extrême en terme de dimensionnement du fait des conditions de sol locales. L'article présente le processus d'élaboration d'une solution permettant un système de fondation sûr, l'analyse des pieux testés, les modèles de construction appliqués et résume le processus de mise en œuvre de la fondation.

Keywords: pile foundation, settlements, organic soil, observational method,

1. INTRODUCTION

In recent years one of the biggest companies in segment on food products in Central and Eastern Europe decided to invest in new production and logistics facilities in 4 locations in Poland. Each facility consists of a new production building together with a logistics centre. The heart of each newly developed logistics centre is an automatic high bay warehouse (so-called SILO).
In this article, an example of one specific SILO foundation solutions will be presented with a description of concept phase design and final applied solution together with a monitoring system. The presented case refers to SILO with dimensions ca. 120 x 50 x 35 m and capacity ca. 30 000 pallets.

2. STRUCTURE CHARACTERISTICS

The warehouse is self-supporting steel rack structure usually with a height between 30 to 40 m. Goods are being stored mostly on pallets lifted by automated cranes. The whole system is fully automated and requires fulfilling very strict criteria on loads distribution and allowable deformations. Computer system responsible for warehouse operation ensure equally spreading the loads on racks to achieve uniform load distribution on the foundation slab but to guarantee safe and effective operations for the system lifetime, foundation deformation criteria specified by technology supplier or European Material Handling Federation (FEM-EUR) had also to be fulfilled.

Figure 1. Example of SILO structure (www. kocherregalbau.com)

For the presented case with SILO height ca. 35 m technology supplier specified foundation plate allowable angular distortion to be lower than 1/2000 both in longitudinal and transversal direction. Additionally, maximum settlement in the operation period (ca. 30 years) should be limited below 3 cm to limit the potential cost impact of structural compensation elements.

3. GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

The area of high storage warehouse is located in the region of Central Poland. The scope of geological investigation has been divided into two campaigns ie. preliminary and final. Preliminary geological surveys included execution of 15 boreholes up to depth ca. 12.0m below ground surface and 4 CPTu's. Analysis of the preliminary geological survey showed that to ensure strict requirements of angular distortion it is necessary to conduct more complex geotechnical survey. Final investigations contain in-situ investigations ie. geological boreholes (up to 60m below ground level), CPT/CPTu, DMT, FVT.
The laboratory investigations contained: shear strength tests ie. CD/CU triaxial tests (with measurement of small strain stiffness), physical properties investigations (unit weight, natural moisture content, Atterberg limits, carbonate content, total organic content), compressibility investigations: oedometer tests.

2.1. Results of geological investigations

Based on investigation results in the substratum five soil layers were distinguished and are discussed in the following section.
First layer is semi-compacted uncontrolled artificial fill with varying from 0,5 up to 1,5m thickness. The layer consist of bricks, cement treated sand, slag, stones e.t.c.
Artificial fill is underlined by high compressible organic Holocene soil – peat (I). The organic content (I_{OM}) varies from 15 up to 84%, undrained

shear strength (S_u) based on FVT investigations varies from 10 up to 60kPa.

Third layer is represented by dense / very dense medium sands with gravel particles (II). The thickness varies from 9m to 15m. The sandy layer is stratified with soft to firm organic mud.

The below there are two organic layers ie. organic mud (III) and gyttja (IV). The organic content of organic mud varies from 5 to 20%, it's undrained shear strength is ca. 150kPa. Gyttja is a high compressible soil characterized by gel-like consistency, with lake-river genesis. Gyttja has a two-phase structure, consisting of two equal components ie. liquid, based on mineralized water and solid on calcite and organic content (Maćkowska, 2011). Its organic content varies from 5 up to 30%, calcium carbonates from 5 to 40%. The thickness of the layer based on neighbouring deep wells drill logs reach 75m. During the site investigations, 20 undistributed samples of the organic mud and gyttja were collected. The piezometric water level has been recorded at an average depth of 1.0m b.g.l. (83.5m A.S.L.), showing pressurization on the bottom of the shallow peat layer.

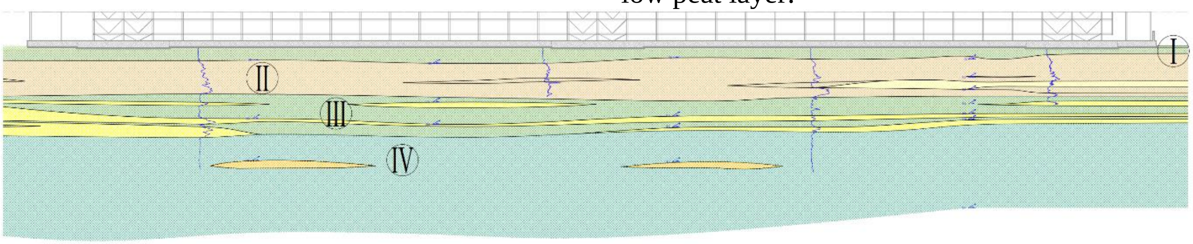

Figure 2. Geological cross-section

2.2. Constitutive models

To ensure accurate settlement calculation the choice of proper constitutive law was important. In this paper, the description of the mechanical properties of soils and structure elements was elaborated using the following constitutive models. Hardening Soil (HS) (Schanz, Vermeer & Bonnier, 1999) and Hardening Soil with small strain stiffness (HSs) (Benz, 2006) are models based on nonlinear stress-strain relationship. In the models, the stiffness is stress dependent different for initial loading and un/reloading. In the settlements prediction, the models were used to simulate Gyttja (III, IV) and sandy soils (II).

The Soft Soil (SS) model is a Cam-Clay type model. It is characterized by a logarithmic stress-strain relationship being proper to simulate compression behaviour of soft soil ie. peat, organic mud. The SS model was used to model shallow organic peat (I).

For the simulation of laboratory test, Plaxis Soil Test tool has been used.

Table 1. Summary of FEM 2D analysis results

Layer *(stratum)*	γ_{sat} (kN/m^3)	ϕ (°)	c (kPa)	E_{oed} (MPa)	E_{50} (MPa)	E_{ur} (MPa)	G_0 (MPa)	$\gamma_{0.7}$	λ^*	κ^*
Engineering Fill	20.0	22	5	60	60	150	-	-	-	-
Peat (I)	12.8	20	16	-	-	-	-	-	0.205	0.05
Organic mud	15.5	14	12.4	10.5	10.5	31.5	-	-	-	-
Organic mud / Gyttja		14	12.4	18.5	18.5	55.1	-	-	-	-
Gyttja (K3-IV)	13.8	18.5	17.8	14.7	14.7	44.1	168	10^{-5}	-	-
Gyttja (K5-IV)		11.7	23.4	47	47	147	135	10^{-5}		
MSa (II)	20.0	39	0.1	>100	125	375	-	-	-	-

4. PRELIMINARY FOUNDATION CONCEPT

The preliminary foundation concept contained three different foundation solutions. Two solutions based on CFA piles with diameter 650mm, longitudinal and cross spacing adjusted to rack support spacing (4.44 x 3.19m) with a variable length from 33 (solution I) to 26m (solution II).
The third solution (III) based on vibrex piles and CSC (screw displacement) columns. The vibrex piles with diameter 400mm, 7.5m long are doubled in number compare to piles in former solutions (I and II). Additionally to ensure quasi-uniform stiffness of deep substratum CSC columns with diameter 250mm, ca. 15m long in the square grid were designed.
For each design solution, the FEM models in Plaxis 2D has been elaborated. Additionally for all solutions calculations taking into account preloading (prior to rack erection) up to 40kPa (a) and 60kPa (b) has been performed. Summary of analysis results is given in table 2. Analysed solutions criteria of maximum allowable settlements are fulfilled but angular distortion criteria could not be fully proven using a simplified approach. On this stage solution II (26 m CFA piles) was recommended to the Client as the best risk-cost compromise.

Table 2. Summary of FEM 2D analysis results

Solution	s_{max} (cm)		Δs/L<1/2000 (Y/N)	
	HS	HSs	HS	HSs
CFA - I	3.52	2.14	N	N
CFA - Ia	2.44	1.11	Y	Y
CFA - Ib	2.72	1.54	Y	Y
CFA - II	3.92	2.40	N	N
CFA - IIa	2.81	1.28	Y	Y
CFA - IIb	3.10	1.78	Y	Y
CSC - III	4.97	3.25	N	N
CSC - IIIa	4.32	2.73	N	N
CSC - IIIb	3.63	2.17	N	N

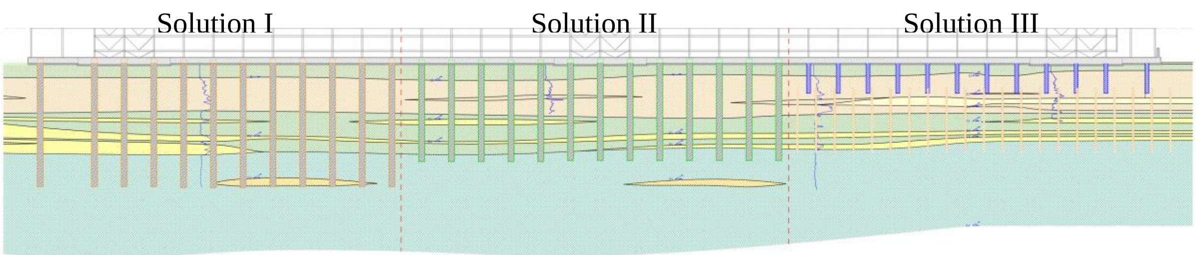

Figure 3. SILO longitudinal cross-section with 3 concept solutions

5. FINAL FOUNDATION CONCEPT

Based on preliminary foundation concept solutions and related to each of them total costs of investment (geotechnical and structural works) client evaluated the KPI's and as a result, decided to increase SILO capacity by 30% in order to keep required profitability. Moreover, due to a tight schedule, no preloading prior to rack erection was possible and due to the cost of structural settlements compensation elements maximum operational settlements of the structure should be reduced below 5 cm (preferably below 3 cm if possible). Those two conditions created a need for redesigning foundation solutions once again. Using previously developed FEM models structure was reanalysed using new assumptions. With presented above 3 possible solutions none of them had fulfilled SILO slab deformation criteria with increased load and limited construction time. Two new CPRF solutions were therefore analysed. First of them using CFA 800 mm diam. piles reaching 36 m. Second, analysed solution was using FDP piles 500 mm diam. piles reaching 40 m.
On this stage once again load was applied as a uniform area load equal to 80 kPa on the slab surface. Additionally, the 3D model was analysed for the first solution.

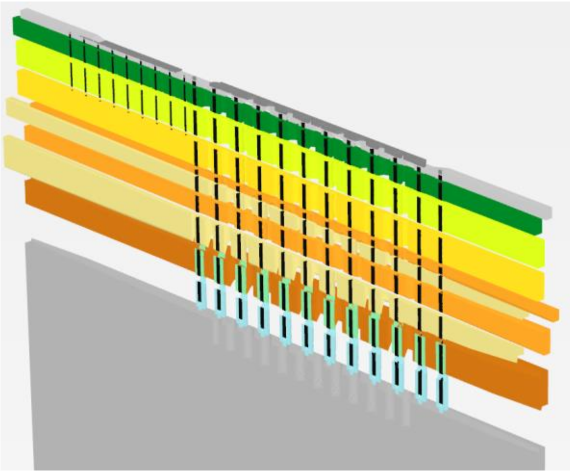

Figure 4. 3D FEM model for CFA 800 L=36 m solution

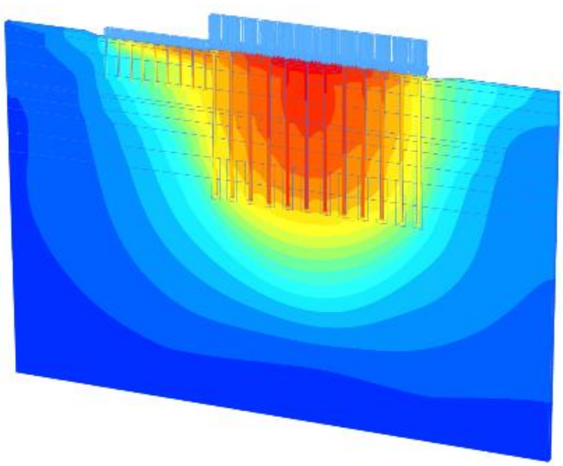

Figure 5. 3D FEM model results for K3 gyttja parameters and HSs constitutive model

For both solutions, the 2D FEM model was analysed including sensitivity analysis for gyttja parameters and applied constitutive models (HS and HSs). Based on gyttja triaxial test results two representative types of samples can be distinguished. First one is gyttja with natural moisture ~ 110-120% (Samples K3) and ~30-40% (Samples K5). The analysis was run using both extreme Gyttja soil stiffness parameters to evaluate the risks of the project.

Table 3. Summary of FEM 2D and 3 D analysis results

Solution	**s_{max} (cm)**		**Δs/L<1/2000 (Y/N)**	
	HS	HSs	HS	HSs
CFA/K5	3.2	2.5	N	Y
CFA/K3	4.9	3.4	N	N
CFA/3D/K3	5.0	3.3	N	Y
FDP/K5	2.8	2.5	Y	Y
FDP/K3	4.4	3.0	N	N

Summary of analysis results is given in table 3. For both analysed solutions criteria of maximum allowable settlements are fulfilled but angular distortion criteria could not be fully proven. Nevertheless taking into account safe side assumptions (uniform area load and extreme values of gyttja stiffness parameters) and simplified 2D analysis it was decided to investigate more precisely behaviour of both solutions, keeping in mind that applied pile installation techniques are reaching their lengths limits.

6. PRELIMINARY FIELD TESTS

In order to distinguish which of the above-analysed solution will perform better, static load tests were designed and performed for CFA 800 L=36 m and FDP 500 L=40 m piles. Static load test (SLT) results were also planned as a basis for final numerical model calibration on executive design elaboration stage. Test piles were located in two areas (BHA and BHB) where according to soil investigations the biggest difference in boreholes profiles was recognized. In each location, three test piles were executed (one CFA and two FDP) together with a group of anchor piles (Figure 5).

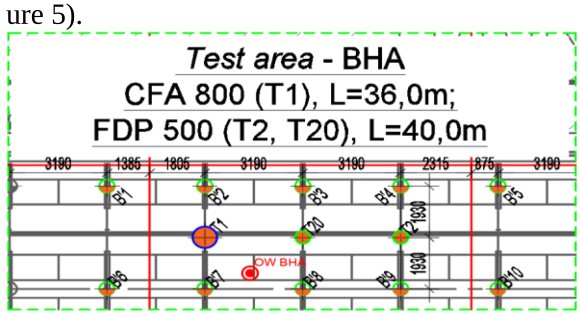

Figure 6. Test piles layout in area BHA

Due to the presence of very dense sand layer from 10 down to 20 m b.g.l. for FDP piles installation predrilling was necessary. Two predrilling methods were applied on test phase both using CFA auger without spoil extraction (drill-in drill-out mode) but with different predrill diameter. Test piles were instrumented with extensometers gauges in order to separate shaft and base mobilized resistance. The testing procedure was adequately adopted to designed loads and soil conditions (Table 4) with a maximum load reaching 4000 kN, where pile working load was 1700 kN.

Table 4. Static load test procedure.

Load (kN)	Time on step (min.)	stabilization criteria (Y/N)
350 kN	20	Y
700 kN	20	Y
1050 kN	20	Y
1700 kN	2880	Y
700 kN	20	N
0 kN	20	Y
…	…	…
1700 kN	60	Y
…	…	…
3100 kN	60	Y
…	…	…
4000 kN	60	Y
…	…	…
1700 kN	5	N
0 kN	20	Y

Figure 7. Instrumented pile head during SLT

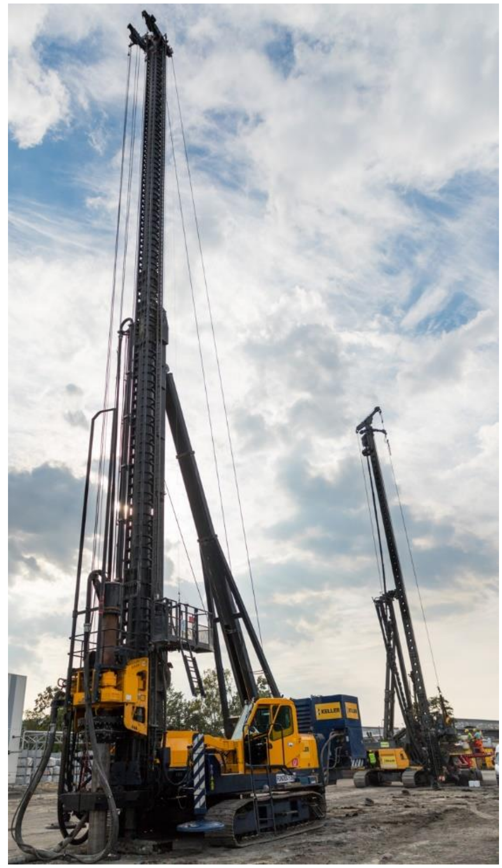

Figure 8. Installation of FDP 40m test pile

7. RESULTS OF PILE TESTS AND FINAL DESIGN

After test piles execution when required concrete strength was achieved SLT were performed. On Figure 9 load-settlements curves are presented for 4 tested piles.

For piles, FDP T2 and T8, where larger predrill auger was used both piles did not reach maximum load. Remaining 4 piles (2xCFA and 2xFDP) response very stiff and presented similar uniform stiffness, therefore solution based on FDP 500 mm diam. Piles with smaller predrill diam. was chosen for the final design.

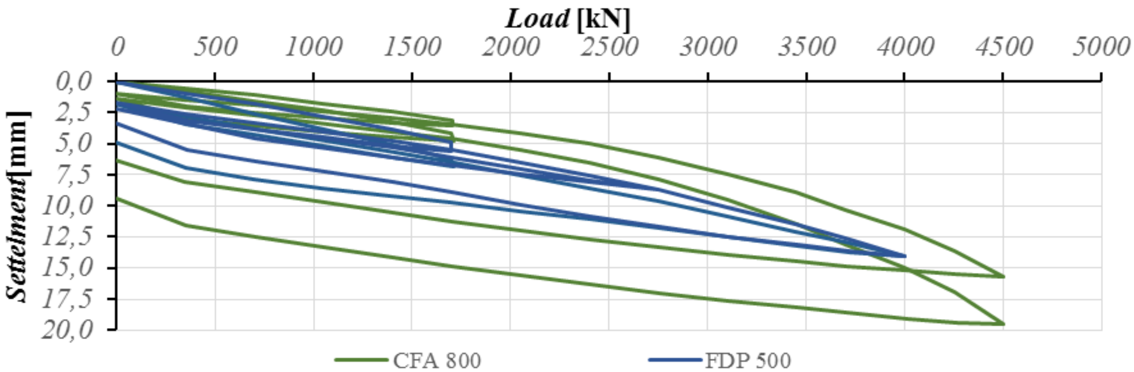

Figure 9. SLT results comparison

Based on real piles behaviour soil constitutive models and its strength stiffness parameters were calibrated for final design analysis (Fig. 9). SLT presented much stiffer response in sands layer than previously assumed in FEM analysis additionally minor adjustments have been done to gyttja parameters. Achieved model calibration accuracy is presented on Fig. 10.

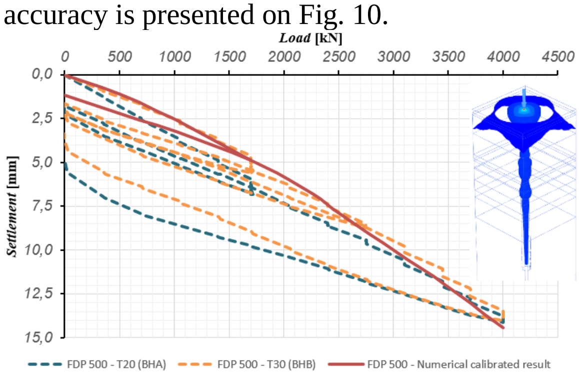

Figure 10. Model calibration results and 3D test pile model

Based on calibrated soil constitutive models detailed analysis of SILO foundation was done including precise input load data (punctual loads) and influence of neighbouring objects (SILO picking and loading buildings with access roads and possible future SILO extension). Moreover, soil parameters (strength and deformations characteristic) sensitivity analysis was done for all models by implementing 25% and 40% reduction on soil models parameters. Additionally for comparison with previous analysis slab load was modelled as a uniform area load equal to 80 kPa (showing upper estimations as per Fig. 12). Due to difficult soil conditions together with strict settlements and angular distortion requirements, the decision was made to introduce the observational method (OM). According to Eurocode 7, it is appropriate to apply the abovementioned approach when "*prediction of geotechnical behaviour is difficult*", however, the code contains no details for geo-engineers. In the following design advice and instructions found in Patel et al. (2007) has been applied.

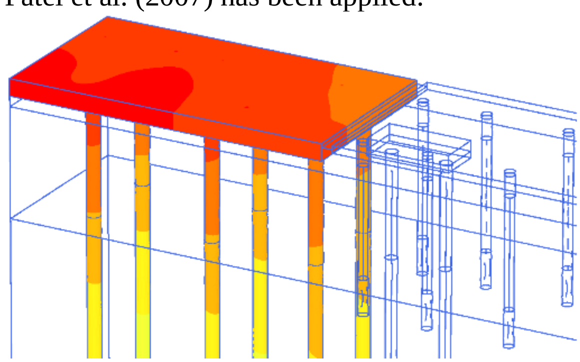

Figure 11. Example 3D SILO foundation model including picking area building

Keeping in mind that applied foundation system is unique for such strict structure deformation requirements additional provision was done in the design agreeing with client and SILO technology supplier. Based on OM approach, multistage application of loads was applied. The SILO load for first 3 years of operation was reduced up to 70% of total designed load At the same time, SILO slab deformation monitoring program was included in the design in 10 years' time perspective.

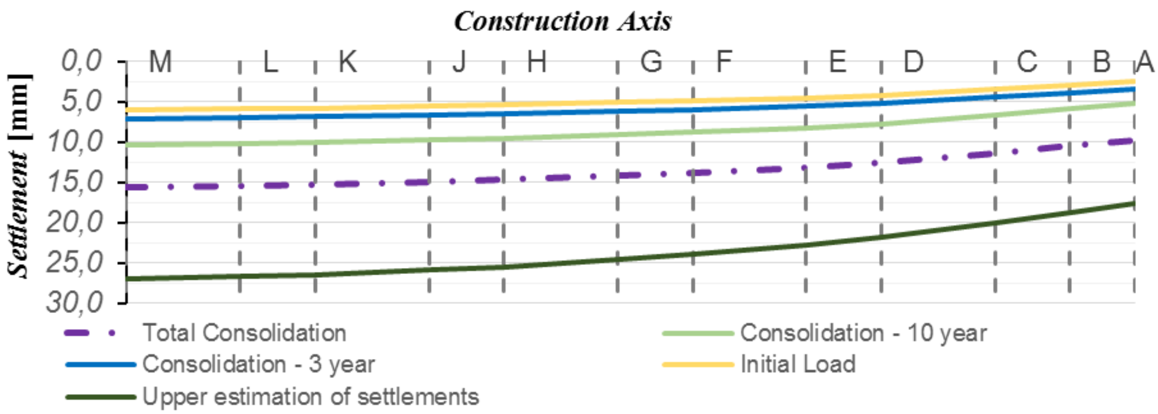

Figure 12. SILO foundation settlement prediction

The final analysis resulted in SILO foundation deformation prediction in the lifetime period including separate deformation values at important operational stages (initial loading, 3 years operation, 10 years operation, total consolidation). Detailed limits of acceptable behaviour together with scheduling controls steps and plan of interventions was elaborated

8. CONCLUSIONS

The presented case study of industrial building foundation design shows a good example of co-operation between client, technology supplier, structural designer, geotechnical designer and contractor. Geotechnics with its cost being one of the key factors for the project “to be or not to be” when involved on early stage can help to find an optimal technical and economical solution and drive the project to execution. Constantly changing business environment forces designers to redefine solutions in order to provide tailored solutions for specific problems. Presence of organic soils required applying detailed analysis on design concept phase and additionally introducing the observational method in the final design.

Currently SILO building is at the beginning of construction process with its steel structure erection scheduled for first half of 2019. The monitoring program when implemented together with the design control steps and optional interventions plan can assure safe object operation in design lifetime. Moreover, it will provide valuable data for design calculation verification and optional future SILO extension foundation design.

9. ACKNOWLEDGMENTS

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